US009741894B2

(12) **United States Patent**
Adibi et al.

(10) **Patent No.: US 9,741,894 B2**
(45) **Date of Patent: Aug. 22, 2017**

(54) **ION IMPLANT SYSTEM HAVING GRID ASSEMBLY**

(71) Applicant: **Intevac, Inc.**, Santa Clara, CA (US)

(72) Inventors: **Babak Adibi**, Los Altos, CA (US); **Moon Chun**, San Jose, CA (US)

(73) Assignee: **INTEVAC, INC.**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/054,049**

(22) Filed: **Feb. 25, 2016**

(65) **Prior Publication Data**

US 2016/0181465 A1 Jun. 23, 2016

Related U.S. Application Data

(62) Division of application No. 14/510,109, filed on Oct. 8, 2014, now Pat. No. 9,303,314, which is a division
(Continued)

(51) **Int. Cl.**
H01L 31/18 (2006.01)
C23C 14/04 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01L 31/1876*** (2013.01); ***C23C 14/042*** (2013.01); ***C23C 14/48*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H01L 21/2236; H01L 21/67069; H01L 31/068; H01L 31/0682; H01L 31/1804; H01L 31/1864; H01L 31/1876
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,607,450 A 9/1971 Kiewit
3,786,359 A 1/1974 King
(Continued)

FOREIGN PATENT DOCUMENTS

CN 1198597 A 11/1998
CN 1404619 A 3/2003
(Continued)

OTHER PUBLICATIONS

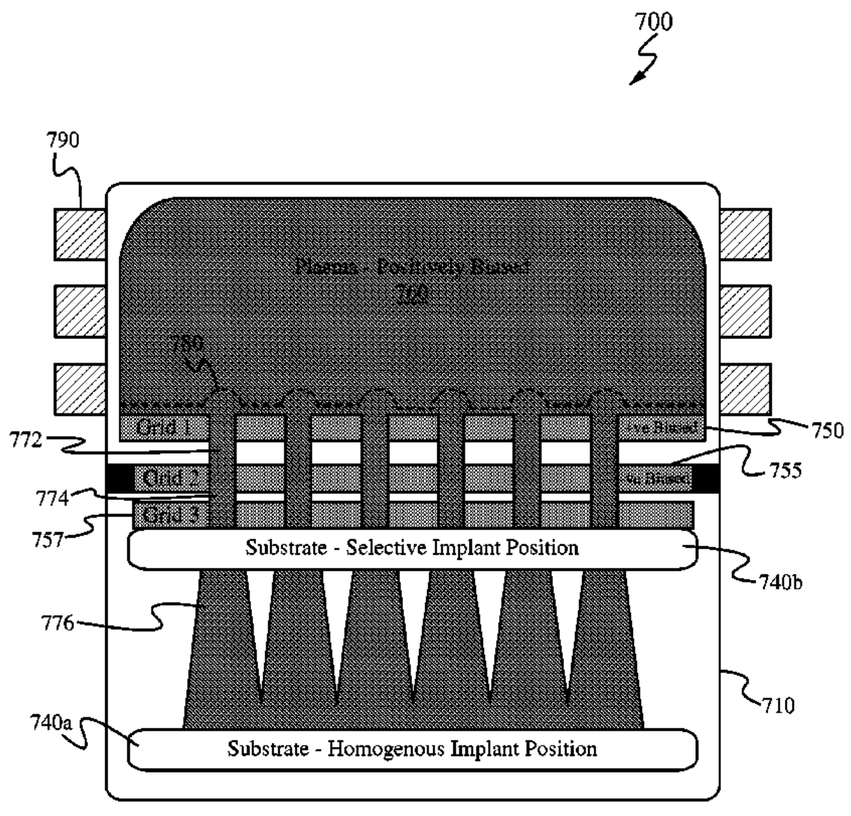
Anders, "Plasma and Ion Sources in Large Area Coating: A Review", Surface Coatings & Technology, Nov. 21, 2005, vol. 200, Issues: 5-6, pp. 1893-1906, Berkeley CA.
(Continued)

Primary Examiner — Edward Chin
(74) *Attorney, Agent, or Firm* — Joseph Bach, Esq.; Womble Carlyle Sandridge & Rice LLP

(57) **ABSTRACT**

An ion implantation system having a grid assembly. The system includes a plasma source configured to provide plasma in a plasma region; a first grid plate having a plurality of apertures configured to allow ions from the plasma region to pass therethrough, wherein the first grid plate is configured to be biased by a power supply; a second grid plate having a plurality of apertures configured to allow the ions to pass therethrough subsequent to the ions passing through the first grid plate, wherein the second grid plate is configured to be biased by a power supply; and a substrate holder configured to support a substrate in a position where the substrate is implanted with the ions subsequent to the ions passing through the second grid plate.

7 Claims, 10 Drawing Sheets



Related U.S. Application Data

of application No. 13/363,341, filed on Jan. 31, 2012, now Pat. No. 8,997,688, which is a division of application No. 12/821,053, filed on Jun. 22, 2010, now Pat. No. 8,749,053.

(60) Provisional application No. 61/219,379, filed on Jun. 23, 2009.

(51) **Int. Cl.**

C23C 14/48	(2006.01)
H01J 37/32	(2006.01)
H01L 21/223	(2006.01)
H01J 37/18	(2006.01)
H01J 37/317	(2006.01)
H01L 31/068	(2012.01)

(52) **U.S. Cl.**

CPC ***H01J 37/185*** (2013.01); ***H01J 37/3171*** (2013.01); ***H01J 37/32412*** (2013.01); ***H01J 37/32422*** (2013.01); ***H01L 21/2236*** (2013.01); ***H01L 31/068*** (2013.01); ***H01L 31/0682*** (2013.01); ***H01L 31/1804*** (2013.01); ***H01L 31/1864*** (2013.01); *H01J 2237/0437* (2013.01); *H01J 2237/184* (2013.01); *H01J 2237/201* (2013.01); *H01J 2237/327* (2013.01); *H01J 2237/3365* (2013.01); *Y02E 10/547* (2013.01); *Y02P 70/521* (2015.11)

(58) **Field of Classification Search**

USPC ..... 118/723 R; 204/192.12, 192.15, 192.17, 204/298.06, 298.11, 298.16, 298.26; 427/569

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,790,412	A	2/1974	Moline	
3,948,682	A	4/1976	Bordina et al.	
3,969,163	A	7/1976	Wakefield	
3,969,746	A	7/1976	Kendall et al.	
3,976,508	A	8/1976	Mlavsky	
4,001,864	A	1/1977	Gibbons	
4,004,949	A	1/1977	Lesk	
4,021,276	A	5/1977	Cho et al.	
4,029,518	A	6/1977	Matsutani et al.	
4,056,404	A	11/1977	Garone et al.	
4,070,205	A	1/1978	Rahilly	
4,070,689	A	1/1978	Coleman et al.	
4,072,541	A	2/1978	Meulenberg, Jr. et al.	
4,086,102	A	4/1978	King	
4,090,213	A	5/1978	Maserjian et al.	
4,095,329	A	6/1978	Ravi	
4,116,717	A	9/1978	Rahilly	
RE29,833	E	11/1978	Mlavsky	
4,131,486	A	12/1978	Brandhorst, Jr.	
4,131,488	A	12/1978	Lesk et al.	
4,141,756	A	2/1979	Chiang et al.	
4,144,094	A	3/1979	Coleman et al.	
4,152,536	A	5/1979	Ravi	
4,152,824	A	5/1979	Gonsiorawski	
4,179,311	A	12/1979	Athanas	
4,219,830	A	8/1980	Gibbons	
4,227,941	A	10/1980	Bozler et al.	
4,253,881	A	3/1981	Hezel	
4,273,950	A	6/1981	Chitre	
4,295,002	A	10/1981	Chappell et al.	
4,301,592	A	11/1981	Lin	
4,322,571	A	3/1982	Stanbery	
4,353,160	A	10/1982	Armini et al.	
RE31,151	E	2/1983	King	
4,377,722	A	3/1983	Wested	
4,379,944	A	4/1983	Borden et al.	
4,404,422	A	9/1983	Green et al.	
4,421,577	A	12/1983	Spicer	
4,428,783	A	1/1984	Gessert	
4,448,865	A	5/1984	Bohlen et al.	
4,449,286	A	5/1984	Dahlberg	
4,456,489	A	6/1984	Wu	
4,479,027	A	10/1984	Todorof	
4,490,573	A	12/1984	Gibbons	
4,495,375	A	1/1985	Rickus et al.	
4,522,657	A	6/1985	Rohatgi et al.	
4,523,971	A	6/1985	Cuomo et al.	
4,524,237	A	6/1985	Ross et al.	
4,533,831	A	8/1985	Itoh et al.	
4,539,431	A	9/1985	Moddel et al.	
4,540,843	A	9/1985	Gochermann et al.	
4,542,256	A	9/1985	Wiedeman	
4,581,620	A	4/1986	Yamazaki et al.	
4,587,430	A	5/1986	Adler	
4,589,191	A	5/1986	Green et al.	
4,633,138	A	12/1986	Tokiguchi et al.	
4,665,277	A	5/1987	Sah et al.	
4,667,060	A	5/1987	Spitzer	
4,676,845	A	6/1987	Spitzer	
4,681,983	A	7/1987	Markvart et al.	
4,719,355	A	1/1988	Meyers et al.	
4,737,688	A	4/1988	Collins et al.	
4,742,381	A	5/1988	Fujii	
4,758,525	A	7/1988	Kida et al.	
4,828,628	A	5/1989	Hezel et al.	
4,830,678	A	5/1989	Todorof et al.	
4,834,805	A	5/1989	Erbert	
4,847,504	A	7/1989	Aitken	
4,886,555	A	12/1989	Hackstein et al.	
4,900,369	A	2/1990	Hezel et al.	
4,927,770	A	5/1990	Swanson	
4,933,021	A	6/1990	Swanson	
4,933,022	A	6/1990	Swanson	
4,967,088	A	10/1990	Stengl et al.	
5,009,720	A	4/1991	Hokuyo et al.	
5,112,409	A	5/1992	Warfield et al.	
5,125,983	A	6/1992	Cummings	
5,132,544	A	7/1992	Glavish	
5,136,171	A	8/1992	Leung et al.	
5,290,367	A	3/1994	Hayashi et al.	
5,306,647	A	4/1994	Lehmann et al.	
5,330,584	A	7/1994	Saga et al.	
5,340,454	A	8/1994	Schaefer et al.	
5,356,488	A	10/1994	Hezel	
5,374,456	A	12/1994	Matossian et al.	
5,391,886	A	2/1995	Yamada et al.	
5,421,889	A	6/1995	Pollock et al.	
5,516,725	A	5/1996	Chang et al.	
5,554,854	A	9/1996	Blake	
5,583,368	A	12/1996	Kenney	
H1637	H	3/1997	Offord et al.	
5,641,362	A	6/1997	Meier	
5,646,488	A *	7/1997	Warburton	G21K 1/10 315/111.21
5,693,376	A	12/1997	Fetherston et al.	
5,760,405	A	6/1998	King et al.	
5,831,321	A	11/1998	Nagayama	
5,883,391	A	3/1999	Adibi et al.	
5,885,896	A	3/1999	Thakur et al.	
5,907,158	A	5/1999	Nasser-Ghodsi et al.	
5,932,882	A	8/1999	England et al.	
5,935,345	A	8/1999	Kuznicki	
5,945,012	A	8/1999	Chan	
5,963,801	A	10/1999	Aronowitz et al.	
5,969,366	A	10/1999	England et al.	
5,985,742	A	11/1999	Henley et al.	
5,988,103	A	11/1999	Fetherston et al.	
5,994,207	A	11/1999	Henley et al.	
5,998,282	A	12/1999	Lukaszek	
5,999,268	A	12/1999	Yonezawa et al.	
6,006,253	A	12/1999	Kumar et al.	
6,010,579	A	1/2000	Henley et al.	
6,013,563	A	1/2000	Henley et al.	
6,016,036	A	1/2000	Brailove	

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,033,974	A	3/2000	Henley et al.	
6,034,321	A	3/2000	Jenkins	
6,048,411	A	4/2000	Henley et al.	
6,051,073	A	4/2000	Chu et al.	
6,060,718	A	5/2000	Brailove et al.	
6,083,324	A	7/2000	Henley et al.	
6,084,175	A	7/2000	Perry et al.	
6,091,021	A	7/2000	Ruby et al.	
6,092,485	A	7/2000	Ando et al.	
6,093,625	A	7/2000	Wagner et al.	
6,103,599	A	8/2000	Henley et al.	
6,113,735	A	9/2000	Chu et al.	
6,120,660	A	9/2000	Chu et al.	
6,130,380	A	10/2000	Nakamura	
6,138,606	A	10/2000	Ling	
6,146,462	A	11/2000	Yializis et al.	
6,146,979	A	11/2000	Henley et al.	
6,150,708	A	11/2000	Gardner et al.	
6,153,524	A	11/2000	Henley et al.	
6,155,909	A	12/2000	Henley et al.	
6,159,824	A	12/2000	Henley et al.	
6,159,825	A	12/2000	Henley et al.	
6,162,705	A	12/2000	Henley et al.	
6,171,965	B1	1/2001	Kang et al.	
6,180,496	B1	1/2001	Farrens et al.	
6,184,111	B1	2/2001	Henley et al.	
6,186,091	B1	2/2001	Chu et al.	
6,200,883	B1	3/2001	Taylor et al.	
6,204,151	B1	3/2001	Malik et al.	
6,206,973	B1	3/2001	Bailey et al.	
6,207,005	B1	3/2001	Henley et al.	
6,213,050	B1	4/2001	Liu et al.	
6,217,724	B1	4/2001	Chu et al.	
6,221,740	B1	4/2001	Bryan et al.	
6,221,774	B1	4/2001	Malik	
6,228,176	B1	5/2001	Chu et al.	
6,238,582	B1	5/2001	Williams et al.	
6,245,161	B1	6/2001	Henley et al.	
6,248,649	B1	6/2001	Henley et al.	
6,258,173	B1	7/2001	Kirimura et al.	
6,263,941	B1	7/2001	Bryan et al.	
6,265,328	B1	7/2001	Henley et al.	
6,269,765	B1	8/2001	Chu et al.	
6,271,566	B1	8/2001	Tsuchiaki	
6,274,459	B1	8/2001	Chan	
6,281,428	B1	8/2001	Chiu et al.	
6,287,941	B1	9/2001	Kang et al.	
6,290,804	B1	9/2001	Henley et al.	
6,291,313	B1	9/2001	Henley et al.	
6,291,314	B1	9/2001	Henley et al.	
6,291,326	B1	9/2001	Henley et al.	
6,294,434	B1	9/2001	Tseng	
6,300,227	B1	10/2001	Liu et al.	
6,313,905	B1	11/2001	Brugger et al.	
6,321,134	B1	11/2001	Henley et al.	
6,335,534	B1	1/2002	Suguro et al.	
6,338,313	B1	1/2002	Chan	
6,365,492	B1	4/2002	Suguro et al.	
6,383,876	B1	5/2002	Son et al.	
6,391,740	B1	5/2002	Cheung et al.	
6,417,515	B1	7/2002	Barrett et al.	
6,429,037	B1	8/2002	Wenham et al.	
6,448,152	B1	9/2002	Henley et al.	
6,458,430	B1	10/2002	Bernstein et al.	
6,458,723	B1	10/2002	Henley et al.	
6,468,884	B2	10/2002	Miyake et al.	
6,476,313	B2	11/2002	Kawano	
6,486,478	B1	11/2002	Libby et al.	
6,489,241	B1	12/2002	Thilderkvist et al.	
6,495,010	B2	12/2002	Sferlazzo	
6,500,732	B1	12/2002	Henley et al.	
6,507,689	B2	1/2003	Tirloni et al.	
6,534,381	B2	3/2003	Cheung et al.	
6,544,862	B1	4/2003	Bryan	
6,552,259	B1	4/2003	Hosomi et al.	
6,552,414	B1	4/2003	Horzel et al.	
6,594,579	B1	7/2003	Lowrey et al.	
6,600,180	B1	7/2003	Ueno et al.	
6,604,033	B1	8/2003	Banet et al.	
6,611,740	B2	8/2003	Lowrey et al.	
6,613,974	B2	9/2003	Husher	
6,632,324	B2	10/2003	Chan	
6,636,790	B1	10/2003	Lightner et al.	
6,660,928	B1	12/2003	Patton et al.	
6,732,031	B1	5/2004	Lightner et al.	
6,752,912	B1 *	6/2004	Sandhu	C23C 14/345 204/192.12
6,759,807	B2	7/2004	Wahlin	
6,767,439	B2	7/2004	Park	
6,780,759	B2	8/2004	Farrens et al.	
6,787,693	B2	9/2004	Lizotte	
6,825,102	B1	11/2004	Bedell	
6,827,824	B1 *	12/2004	Blalock	C23C 14/345 204/192.12
6,874,515	B2	4/2005	Ishihara et al.	
6,878,898	B2 *	4/2005	Hogan	H01J 37/32431 156/345.39
6,949,895	B2	9/2005	DiVergilio et al.	
6,968,630	B2	11/2005	Kato et al.	
7,011,733	B2 *	3/2006	Sandhu	C23C 14/345 204/192.12
7,022,984	B1	4/2006	Rathmell et al.	
7,045,793	B2	5/2006	Wahlin	
7,066,703	B2	6/2006	Johnson	
7,078,317	B2	7/2006	Henley	
7,081,186	B2	7/2006	Ehiasarian et al.	
7,094,666	B2	8/2006	Henley et al.	
7,098,394	B2	8/2006	Armer et al.	
7,147,709	B1	12/2006	Ong et al.	
7,166,520	B1	1/2007	Henley	
7,174,243	B1	2/2007	Lightner et al.	
7,225,047	B2	5/2007	Al-Bayati et al.	
7,225,065	B1	5/2007	Hunt et al.	
7,228,211	B1	6/2007	Lowrey et al.	
7,250,323	B2	7/2007	Gadeken et al.	
7,339,110	B1	3/2008	Mulligan et al.	
7,354,815	B2	4/2008	Henley	
7,390,724	B2	6/2008	Henley et al.	
7,399,680	B2	7/2008	Henley	
7,427,554	B2	9/2008	Henley et al.	
7,447,574	B1	11/2008	Washicko et al.	
7,477,968	B1	1/2009	Lowrey et al.	
7,479,441	B2	1/2009	Kirk et al.	
7,480,551	B1	1/2009	Lowrey et al.	
7,498,245	B2	3/2009	Aspar et al.	
7,521,699	B2	4/2009	Yamazaki et al.	
7,523,159	B1	4/2009	Williams et al.	
7,532,962	B1	5/2009	Lowrey et al.	
7,532,963	B1	5/2009	Lowrey et al.	
7,547,609	B2	6/2009	Henley	
7,564,042	B2	7/2009	Lee et al.	
7,598,153	B2	10/2009	Henley et al.	
7,611,322	B2	11/2009	Bluck et al.	
7,674,687	B2	3/2010	Henley	
7,701,011	B2	4/2010	Kamath et al.	
7,727,866	B2	6/2010	Bateman et al.	
7,759,220	B2	7/2010	Henley	
7,767,561	B2	8/2010	Hanawa et al.	
7,772,088	B2	8/2010	Henley et al.	
7,776,727	B2	8/2010	Borden	
7,796,849	B2	9/2010	Adibi et al.	
7,862,683	B2 *	1/2011	Fukiage	C23C 16/4405 118/715
7,867,409	B2	1/2011	Brcka	
8,058,156	B2	11/2011	Hanawa et al.	
8,179,530	B2 *	5/2012	Levy	G01N 21/211 356/401
8,286,517	B2 *	10/2012	Lee	B08B 13/00 73/866
8,298,340	B2	10/2012	Fukao et al.	
8,481,923	B1 *	7/2013	Kitamoto	B01D 59/44 250/281
8,697,552	B2	4/2014	Adibi et al.	

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,697,553	B2	4/2014	Adibi et al.	
8,749,053	B2	6/2014	Adibi et al.	
8,871,619	B2	10/2014	Adibi et al.	
8,997,688	B2	4/2015	Adibi et al.	
9,303,314	B2	4/2016	Adibi et al.	
9,318,332	B2	4/2016	Prabhakar et al.	
9,324,598	B2	4/2016	Pederson et al.	
2001/0002584	A1	6/2001	Liu et al.	
2001/0017109	A1	8/2001	Liu et al.	
2001/0020485	A1	9/2001	Ford et al.	
2002/0090758	A1	7/2002	Henley et al.	
2002/0109233	A1	8/2002	Farrar	
2002/0109824	A1	8/2002	Yamaguchi	
2002/0139666	A1	10/2002	Hsueh et al.	
2002/0144725	A1	10/2002	Jordan et al.	
2002/0152057	A1	10/2002	Wang et al.	
2002/0185700	A1	12/2002	Coffa et al.	
2003/0015700	A1	1/2003	Eisenbeiser et al.	
2003/0106643	A1*	6/2003	Tabuchi	C23C 16/24 156/345.35
2003/0116090	A1	6/2003	Chu et al.	
2003/0129045	A1	7/2003	Bonora et al.	
2003/0137050	A1	7/2003	Chambers et al.	
2003/0215991	A1	11/2003	Sohn et al.	
2003/0230986	A1*	12/2003	Horsky	C23C 14/48 315/111.81
2004/0025791	A1	2/2004	Chen et al.	
2004/0025932	A1	2/2004	Husher	
2004/0067644	A1	4/2004	Malik et al.	
2004/0112426	A1	6/2004	Hagino	
2004/0123804	A1	7/2004	Yamazaki et al.	
2004/0185644	A1	9/2004	Shibata et al.	
2004/0187916	A1	9/2004	Hezel	
2004/0198028	A1	10/2004	Tanaka et al.	
2004/0200520	A1	10/2004	Mulligan et al.	
2004/0216993	A1	11/2004	Sandhu	
2004/0232414	A1	11/2004	Suthar et al.	
2005/0045835	A1	3/2005	DiVergilio et al.	
2005/0133084	A1	6/2005	Joge et al.	
2005/0150597	A1	7/2005	Henley et al.	
2005/0163598	A1	7/2005	Yuasa et al.	
2005/0181584	A1	8/2005	Foad et al.	
2005/0183670	A1	8/2005	Grantham et al.	
2005/0205211	A1	9/2005	Singh et al.	
2005/0211170	A1	9/2005	Hanawa et al.	
2005/0214477	A1	9/2005	Hanawa et al.	
2005/0247668	A1	11/2005	Malik et al.	
2005/0266781	A1	12/2005	Jaenen et al.	
2006/0019039	A1	1/2006	Hanawa et al.	
2006/0019477	A1	1/2006	Hanawa et al.	
2006/0037700	A1	2/2006	Shi et al.	
2006/0081180	A1	4/2006	Aoki et al.	
2006/0144335	A1	7/2006	Lee et al.	
2006/0148241	A1	7/2006	Brody et al.	
2006/0157733	A1*	7/2006	Lucovsky	H01L 21/28194 257/192
2006/0166394	A1	7/2006	Kukulka et al.	
2006/0174829	A1	8/2006	An et al.	
2006/0211219	A1	9/2006	Henley et al.	
2006/0234484	A1	10/2006	Lanzerotti et al.	
2006/0252217	A1	11/2006	Rouh et al.	
2006/0279970	A1	12/2006	Kernahan	
2007/0012503	A1	1/2007	Iida	
2007/0029043	A1	2/2007	Henley	
2007/0032044	A1	2/2007	Henley	
2007/0035847	A1	2/2007	Li et al.	
2007/0068624	A1	3/2007	Jeon et al.	
2007/0081138	A1	4/2007	Kerkhof et al.	
2007/0084505	A1	4/2007	Zaidi	
2007/0087574	A1	4/2007	Gupta et al.	
2007/0089833	A1	4/2007	Inouchi et al.	
2007/0119373	A1	5/2007	Kumar et al.	
2007/0132368	A1	6/2007	Kuwahara et al.	
2007/0134840	A1	6/2007	Gadeken et al.	
2007/0148336	A1	6/2007	Bachrach et al.	
2007/0169806	A1	7/2007	Fork et al.	
2007/0181820	A1	8/2007	Hwang et al.	
2007/0181829	A1	8/2007	Tanaka et al.	
2007/0209707	A1	9/2007	Weltman	
2007/0214101	A1	9/2007	Wang et al.	
2007/0217020	A1	9/2007	Li et al.	
2007/0235074	A1	10/2007	Henley et al.	
2007/0249131	A1	10/2007	Allen et al.	
2007/0268089	A1	11/2007	McKenzie et al.	
2007/0275569	A1	11/2007	Moghadam et al.	
2007/0277875	A1	12/2007	Gadkaree et al.	
2007/0281172	A1	12/2007	Couillard et al.	
2007/0281399	A1	12/2007	Cites et al.	
2007/0290283	A1	12/2007	Park et al.	
2008/0000497	A1	1/2008	Verhaverbeke	
2008/0001139	A1	1/2008	Augusto	
2008/0038908	A1	2/2008	Henley	
2008/0044964	A1	2/2008	Kamath et al.	
2008/0078444	A1	4/2008	Atanackovic	
2008/0090392	A1	4/2008	Singh et al.	
2008/0092944	A1	4/2008	Rubin	
2008/0092947	A1	4/2008	Lopatin et al.	
2008/0116397	A1	5/2008	Yoshida et al.	
2008/0121275	A1	5/2008	Ito et al.	
2008/0121276	A1	5/2008	Lopatin et al.	
2008/0128019	A1	6/2008	Lopatin et al.	
2008/0128641	A1	6/2008	Henley et al.	
2008/0164819	A1	7/2008	Hwang et al.	
2008/0179547	A1	7/2008	Henley	
2008/0188011	A1	8/2008	Henley	
2008/0190886	A1	8/2008	Choi et al.	
2008/0206962	A1	8/2008	Henley et al.	
2008/0217554	A1	9/2008	Abe	
2008/0242065	A1*	10/2008	Brcka	H01J 37/32623 438/513
2008/0275546	A1*	11/2008	Storey	A61F 2/0077 623/1.46
2008/0284028	A1	11/2008	Greywall	
2008/0296261	A1*	12/2008	Zhao	H01J 37/32623 216/67
2008/0318168	A1	12/2008	Szot et al.	
2009/0014725	A1	1/2009	Nakanishi	
2009/0042369	A1	2/2009	Henley	
2009/0056807	A1	3/2009	Chen et al.	
2009/0081860	A1	3/2009	Zhou et al.	
2009/0124064	A1	5/2009	England et al.	
2009/0124065	A1	5/2009	England et al.	
2009/0140132	A1	6/2009	Lee et al.	
2009/0142875	A1	6/2009	Borden et al.	
2009/0149001	A1	6/2009	Cites et al.	
2009/0152162	A1	6/2009	Tian et al.	
2009/0162970	A1	6/2009	Yang	
2009/0206275	A1	8/2009	Henley et al.	
2009/0227061	A1	9/2009	Bateman et al.	
2009/0227062	A1	9/2009	Sullivan et al.	
2009/0227094	A1	9/2009	Bateman et al.	
2009/0227095	A1	9/2009	Bateman et al.	
2009/0227097	A1	9/2009	Bateman et al.	
2009/0246706	A1	10/2009	Hendel et al.	
2009/0289197	A1	11/2009	Slocum et al.	
2009/0308439	A1*	12/2009	Adibi	H01L 21/266 136/255
2009/0308440	A1	12/2009	Adibi et al.	
2009/0308450	A1	12/2009	Adibi et al.	
2009/0309039	A1	12/2009	Adibi et al.	
2009/0317937	A1	12/2009	Gupta et al.	
2009/0324369	A1	12/2009	Scollay et al.	
2010/0025821	A1*	2/2010	Ohmi	H01J 37/3222 257/607
2010/0041176	A1	2/2010	Sullivan et al.	
2010/0055874	A1	3/2010	Henley	
2010/0059362	A1	3/2010	Anella	
2010/0062589	A1	3/2010	Anella et al.	
2010/0062674	A1	3/2010	Muraki	
2010/0087028	A1	4/2010	Porthouse et al.	
2010/0096084	A1*	4/2010	Lee	H01L 21/67069 156/345.33
2010/0110239	A1	5/2010	Ramappa et al.	
2010/0124799	A1	5/2010	Blake et al.	

(56) **References Cited**

U.S. PATENT DOCUMENTS

2010/0159120	A1*	6/2010	Dzengeleski	H01J 37/32935 427/8
2010/0167511	A1	7/2010	Leung et al.	
2010/0170440	A9	7/2010	Mizukami et al.	
2010/0178723	A1	7/2010	Henley	
2010/0180945	A1	7/2010	Henley et al.	
2010/0181654	A1*	7/2010	Fujiwara	C23C 16/342 257/632
2010/0184243	A1	7/2010	Low et al.	
2010/0184248	A1	7/2010	Hilali et al.	
2010/0187611	A1	7/2010	Schiwon	
2010/0196626	A1*	8/2010	Choi	C23C 16/4585 427/569
2010/0197125	A1	8/2010	Low et al.	
2010/0206713	A1	8/2010	Li et al.	
2010/0224228	A1	9/2010	Kim et al.	
2010/0229928	A1	9/2010	Zuniga et al.	
2010/0240169	A1	9/2010	Petti et al.	
2010/0240183	A1	9/2010	Narazaki	
2010/0314552	A1	12/2010	Tatemichi et al.	
2010/0323508	A1	12/2010	Adibi et al.	
2011/0011734	A1*	1/2011	Marunaka	C23C 14/32 204/192.11
2011/0027463	A1	2/2011	Riordon et al.	
2011/0097824	A1	4/2011	Berliner et al.	
2011/0116205	A1	5/2011	Schlitz	
2011/0124186	A1	5/2011	Renau et al.	
2011/0135836	A1	6/2011	Hays et al.	
2011/0162703	A1	7/2011	Adibi et al.	
2011/0192993	A1*	8/2011	Chun	H01L 21/266 250/492.21
2011/0272012	A1	11/2011	Heng et al.	
2011/0309050	A1*	12/2011	Iori	H01J 37/32357 216/67
2012/0021136	A1*	1/2012	Dzengeleski	H01J 37/321 427/523
2012/0080082	A1	4/2012	Suh	
2012/0103403	A1	5/2012	Misra et al.	
2012/0118857	A1	5/2012	Tyler et al.	
2012/0122273	A1*	5/2012	Chun	H01L 31/068 438/98
2012/0125259	A1*	5/2012	Adibi	C23C 14/042 118/723 R
2012/0129325	A1	5/2012	Adibi et al.	
2012/0138230	A1	6/2012	Bluck et al.	
2012/0199202	A1	8/2012	Prajapati	
2012/0258606	A1*	10/2012	Holland	H01J 37/32357 438/798
2012/0305063	A1	12/2012	Moslehi et al.	
2013/0008494	A1	1/2013	Bateman	
2013/0115764	A1	5/2013	Pederson et al.	
2014/0166087	A1	6/2014	Hieslmair et al.	
2014/0170795	A1	6/2014	Prabhakar et al.	
2015/0072461	A1	3/2015	Adibi et al.	
2016/0204295	A1	7/2016	Prabhakar et al.	
2016/0233122	A1	8/2016	Pederson et al.	
2016/0322523	A1	11/2016	Hieslmair et al.	
2017/0018318	A1*	1/2017	Radel	H05H 3/06

FOREIGN PATENT DOCUMENTS

CN	1445604	A	10/2003
CN	1622294	A	6/2005
CN	1638015		7/2005
CN	1763916	A	4/2006
CN	101006572	A	7/2007
CN	101055898	A	10/2007
CN	101145569	A	3/2008
CN	101490824	A	7/2009
CN	102099870	A	6/2011
CN	102099923	A	6/2011
CN	102150277	A	8/2011
CN	102150278	A	8/2011
CN	102396068	A	3/2012
CN	102804329	A	11/2012
CN	102834905	A	12/2012
CN	103370769	A	10/2013
CN	104428883	A	3/2015
CN	102804329	B	7/2015
CN	105051910	A	11/2015
CN	102099923	B	4/2016
CN	102834905	B	5/2016
DE	4217428		6/1993
DE	19820152		11/1999
DE	112013006064	T5	8/2015
EP	1973145	A1	9/2008
EP	2304803	A1	4/2011
EP	2308060	A1	4/2011
EP	2319087	A1	5/2011
EP	2319088	A1	5/2011
EP	2409331	A1	1/2012
EP	2446458	A	5/2012
EP	2489757	A2	8/2012
EP	2534674	A1	12/2012
EP	2641266	A1	9/2013
EP	2777069	A2	9/2014
EP	2814051	A1	12/2014
EP	2534674	B1	4/2016
JP	S62-15864	A	1/1987
JP	S62-237766	A	10/1987
JP	63-143876	A	6/1988
JP	H01-290267	A	11/1989
JP	H02-26248	U	2/1990
JP	H02-201972	A	8/1990
JP	H03-180471	A	8/1991
JP	H04-221059	A	8/1992
JP	S57-132373	A	8/1992
JP	H06-13451	A	1/1994
JP	H06-47324	A	2/1994
JP	H07-135329	A	5/1995
JP	8-298247	A	11/1996
JP	H09-321327	A	12/1997
JP	H10-084125	A	3/1998
JP	2000-123778	A	4/2000
JP	2001-189483	A	7/2001
JP	2001-252555	A	9/2001
JP	2001-517562	A	10/2001
JP	2002-043404	A	2/2002
JP	2002-057352		2/2002
JP	2002-083981	A	3/2002
JP	2002-217430	A	8/2002
JP	2002-540548	A	11/2002
JP	2003-279493	A	10/2003
JP	2004-031648	A	1/2004
JP	2004-039751	A	2/2004
JP	2004-193350	A	7/2004
JP	2004-273826	A	9/2004
JP	2005-005376	A	1/2005
JP	2005-026554	A	1/2005
JP	2005-123447	A	5/2005
JP	2005-129597	A	5/2005
JP	2005-322780	A	11/2005
JP	2006-170733	A	6/2006
JP	2006-196752	A	7/2006
JP	2006-310373	A	11/2006
JP	2007-053386	A	3/2007
JP	2007-504622	A	3/2007
JP	2007-207973	A	8/2007
JP	2008-297584	A	12/2008
JP	2009-049443		3/2009
JP	2009-129611	A	6/2009
JP	2009-280835	A	12/2009
JP	2010-141352	A	6/2010
JP	2011-003913	A	1/2011
JP	2011-524638	A	9/2011
JP	2011-524639	A	9/2011
JP	2011-524640	A	9/2011
JP	2011-525301	A	9/2011
JP	2012-521642	A	9/2012
JP	2012-231520	A	11/2012
JP	2012-531520	A	12/2012
JP	2014-502048		1/2014
JP	5520290	B2	6/2014

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

JP	2015-504598	A	2/2015
JP	5875515	B2	3/2016
KR	10-2002-0059187		7/2002
KR	10-2007-0043157	A	7/2002
KR	100759084	B1	9/2007
KR	20110042051	A1	4/2011
KR	20110042052	A	4/2011
KR	20110042053	A1	4/2011
KR	20110050423	A1	5/2011
KR	20120027149	A1	3/2012
KR	20120034664	A1	4/2012
KR	20120137361	A	12/2012
KR	20130129961	A	11/2013
KR	10-1434886	B1	8/2014
KR	10-2014-0110851	A	9/2014
SG	174289	A	10/2011
SG	176547	A1	1/2012
SG	183267	A1	9/2012
SG	186005	A1	12/2012
SG	190332	A1	6/2013
TW	428216	B	4/2001
TW	200847217	A	12/2008
TW	200933797	A	8/2009
TW	201232796	A1	8/2012
TW	201320229	A	5/2013
TW	201436258	A	9/2014
TW	I469368	B	1/2015
TW	I506719	B	11/2015
TW	201606921	A	2/2016
TW	I531077	B	4/2016
WO	99/16111	A1	4/1999
WO	WO02075816	A1	9/2002
WO	WO2006019039	A1	2/2006
WO	WO2007142865		12/2007
WO	WO 2008009889	A1	1/2008
WO	WO2009033134	A2	3/2009
WO	WO2009033134	A3	3/2009
WO	WO2009064867	A2	5/2009
WO	WO2009064867	A3	5/2009
WO	WO2009064872	A2	5/2009
WO	WO2009064872	A3	5/2009
WO	WO2009064875	A1	5/2009
WO	WO2009085948	A2	7/2009
WO	WO2009085948	A3	7/2009
WO	WO2009111665	A2	9/2009
WO	WO2009111665	A3	9/2009
WO	WO2009111666	A2	9/2009
WO	WO2009111666	A3	9/2009
WO	WO2009111667	A2	9/2009
WO	WO2009111667	A3	9/2009
WO	WO2009111668	A2	9/2009
WO	WO2009111668	A3	9/2009
WO	WO2009111668	A9	9/2009
WO	WO2009111669	A2	9/2009
WO	WO2009111669	A3	9/2009
WO	WO2009152365	A1	12/2009
WO	WO2009152368	A1	12/2009
WO	WO2009152375	A1	12/2009
WO	WO2009152378	A1	12/2009
WO	WO2009155498	A2	12/2009
WO	WO2009155498	A3	12/2009
WO	WO2010030588	A2	3/2010
WO	WO2010030645	A2	3/2010
WO	WO2010030645	A3	3/2010
WO	2010/055876	A1	5/2010
WO	WO2010108151	A1	9/2010
WO	WO2010147997	A2	12/2010
WO	WO2011005582	A1	1/2011
WO	WO2011100363	A1	8/2011
WO	WO2012068417	A1	5/2012
WO	2013070978	A2	5/2013
WO	WO2014100043	A1	6/2014
WO	WO2014100506	A1	6/2014
WO	2016/022728	A1	2/2016

OTHER PUBLICATIONS

Armini et al., "A Non-Mass-Analyzed Solar Cell Ion Implanter", Nuclear Instruments and Methods in Physics Research B6 (1985) 94-99, North Holland, Amsterdam, Spire Corporation, Patriots Park, Bedford, Masachusetti 01730, USA.

Chun, M. et al., "Using Solid Phase Epitaxial Re-Growth for Ion Implantation in Solar Cell Fabrications", 26th European Photovoltaic Solar Energy Conference and Exhibition, Sep. 5, 2011 to Sep. 9, 2011, Hamburg (CCH Congress Centre & International Fair), Germany.

Com-Nougue et al., "CW CO2 Laser Annealing Associated with Ion Implantation for Production of Silicon Solar Cell Junctions", Jan. 1982, IEEE, p. 770.

Cornet et al., "A New Algorithm for Charge Deposition for Multiple-Grid Method for PIC Simulations in r-z Cylindrical Coordinates", www.sciencedirect.com, Journal of Computational Physics, Jul. 1, 2007, vol. 225, Issue: 1, pp. 808-828, Sydney, Australia.

Donnelly et al., "Nanopantography: A Method for Parallel Writing of Etched and Deposited Nanopatterns", Oct. 2009, University of Houston, Houston, TX, 36 pages.

Douglas et al., "A Study of the Factors Which Control the Efficiency of Ion-Implanted Silicon Solar Cells", IEEE Transactions on Electron Devices, vol. ED-27, No. 4, Apr. 1980, pp. 792-802.

Eaton Nova (Axcelis) 200E2 H/C Implanter, data sheet, 2 pgs. , Jan. 1990.

Fu et al , "Enhancement of Implantation Energy Using a Conducting Grid in Plasma Immersion Ion Implantation of Dielectric/Polymeric Materials", Review of Scientific Instruments, vol. 74, No. 8, Aug. 2003, pp. 3697-3700.

Goeckner et al., "Plasma Doping for Shallow Junctions", Journal of Vacuum Science and Technology B, vol. 17, Issue 5, Sep. 1999, pp. 2290-2293.

Horzel, J. et al., "A Simple Processing Sequence for Selective Emitters", IEEE, 26th PVSC Conference Record of the Twenty-Sixth Photovoltaic Specialists Conference, Sep. 30-Oct. 3, 1997, Anaheim, CA, pp. 139-142.

"Implantation par Immersion Plasma (PULSION)", Ion Beam Services (IBS), Dec. 2008, ZI Peynier Rousset, France.

Jager-Hezel, K. "Developments for Large-Scale Production of High-Efficiency Silicon Solar Cells," Advances in Solid State Physics, vol. 34, Jan. 1994, pp. 97-113, <http://www.springerlink.com/content/982620t34312416v/>.

Janssens, et al., "Advanced Phosphorus Emitters for High Efficiency SI Solar Cells", 24th European Photovoltaic Solar Energy Conference, Sep. 21-25, 2009, Hamburg, Germany.

Kim, D-M. et al., "Dopant activation after ion shower doping for the fabrication of low-temperature poly-SI TFTs", Thin Solid Films, Elsevier-Sequoia S.A. vol. 475, No. 1-2, Mar. 22, 2005 pp. 342-347.

Kim, H.J. et al., "Construction and characterization of an amorphous silicon flat-panel detector based on ion-shower doping process", Nuclear Instruments & Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment, Elsevier Science B.V., North Holland, vol. 505, No. 1-2, Jun. 1, 2003, pp. 155-158.

Kim, K-S et al., "PH3 Ion Shower Implantation and Rapid Thermal Anneal with Oxide Capping and Its Application to Source and Drain Formation of a Fully Depleted Silicon-on-Insulator Metal Oxide Semiconductor Field Effect Transistor", Japanese Journal of Applied Physics, vol. 43, No. 10, Oct. 1, 2004, pp. 6943-6947.

Kondratenko, S. et al, "Channeling Effects and Quad Chain Implantation Process Optimization for Low Energy Boron Ions," abstract, IEEE Xplore Digital Library, Issue date: Sep. 22-27, 2002, Current version date: Jan. 7, 2004, 1 pg., downloaded from ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=1257941.

Kroner, F. et al., "Phosphorus Ion Shower Doping System for TFT-LCD's", SPIE vol. 3014, 1997, pp. 31-37.

Kwok et al., "One-Step, Non-Contact Pattern Transfer by Direct-Current Plasma Immersion Ion Implantation", Journal of Physics D: Applied Physics, IOP Publishing, vol. 42, No. 19, Sep. 2009, pp. 1-6.

(56) **References Cited**

OTHER PUBLICATIONS

Kwok et al. "One-Step Non-Contact Pattern Transferring by Plasma Based Ion Implantation", Journal of Physics D: Applied Physics, IOP Publishing, vol. 41, No. 22, Oct. 2008, pp. 1-6.
"Leading Semiconductor Manufacturer Selects Axcelis HE3 Ion Implantation Equipment; 300 mm Facility to Choose Axcelis Platform for High Energy Implant," Business Wire, Oct. 17, 2000, 1 pg.
Minnucci et al., "Tailored Emitter, Low-Resistivity, Ion-Implanted Silicon Solar Cells", IEEE Transactions on Electron Devices, vol. ED-27, No. 4, Apr. 1980, pp. 802-806.
Mishima, Y. et al., "Non-mass-separated ion shower doping of polycrystalline silicon", J. Appl. Phys. vol. 75, No. 10, 1994, pp. 4933-4938.
Moon, B.Y. et al., "Fabrication of amorphous silicon p-i-n solar cells using ion shower doping technique", Solar Energy Materials and Solar Cells, vol. 49, No. 1-4, Dec. 1, 1997, pp. 113-119.
Mouhoub, A. et al., "Selective Emitters for Screen Printed Multicrystalline Silicon Solar Cells", Rev. Energ. Ren.: ICPWE, 2003, pp. 83-86.
Nakamoto, I. et al., "Ion Shower Doping System for TFT-LCD's", SPIE vol. 3014, 1997, pp. 31-37.
Neuhaus et al., "Industrial Silicon Wafer Solar Cells", Hindawl Publishing Corp, vol. 2007, pp. 1-15.
Nielsen, "Ion Implanted Polycrystalline Silicon Solar Cells", Physica Scripta, vol. 24, No. 2, Aug. 1, 1981, pp. 390-391.
Nikiforov et al., Large Volume ICP Sources for Plasma-based Accelerators, Korea Elecrtrotechnology Research Institute (KERI), APAC 2004, Gyeongju, Korea.
Nitodas, S.F., et al., "Advantages of single and mixed species chaining for high productivity in high and mid-energy implantation," published Sep. 2002, Ion Implantation Technology, Current version date Jan. 7, 2004, abstract, downloaded from ieeexplore.ieee.org., 1 pg.
Pelletier et al., "Plasma-Based Ion Implantation and Deposition: A Review of Physics, Technology, and Applications", http://www.escholarship.org/uc/item/84k974r2, Lawrence Berkeley National Laboratory, May 16, 2005, pp. 1-69.
Rentsch, et al. "Technology Route Towards Industrial Application of Rear Passivated Silicon Solar Cells", Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion. vol. 1 (2006) pp. 1008-1011, May 2006.
Semiconductor Consulting Service publication: "Process Technology for the 21st Century," Chapter 10-Substrates, Isolation, Well and Transistor Formation, Jan. 1999, downloaded from IC Knowledge.com, http://www.icknowledge.com/our_products/pt21c.html., pp. 10-1-10-4.
Sopian et al., "Plasma Implantation for Emitter and Localized Back Surface Field (BSF) Formation in Silicon Solar Cells", European Journal of Scientific Research, http://www.eurojournals.com/ejsr.htm, ISSN 1450-216X, vol. 24, No. 3, Jan. 2008, pp. 365-372.
Steckl, "Particle-beam Fabrication and in Situ Processing of Integrated Circuits", IEEE Xplore, Dec. 1986, vol. 74, Issue 12.
Szlufcik, J. et al., "Advanced concepts of industrial technologies of crystalline silicon solar cells", Interuniversity Microelectronics Centre (IMEC) Leuven, Beligium, Opto-electronics Review, vol. 8, Issue 4, 2000, pp. 299-306.
Tang et al., "Current Control for Magnetized Plasma in Direct-Current Plasma-Immersion Ion Implantation", American Institute of Physics, Applied Physics Letters, vol. 82, No. 13, Mar. 31, 2003, pp. 2014-2016.
Vervisch et al., "Plasma Immersion Ion Implantation Applied to P+N Junction Solar Cells", CP866, Ion Implantation Technology, American Institute of Physics, vol. 866, Jan. 2006, pp. 253-256.
"Varian Introduces a New High-Energy Ion Implant System for Optimized Performance and Lowest Cost of Ownership," Press Release, Business Wire, Jul. 14, 1999, 1 pg.
Walther, S.R. et al., "Using Multiple Implant Regions to Reduce Development Wafer Usage", Jan. 1, 2006, American Institute of Physics, CP866, Ion Implantation Technology, pp. 409-412.
Wu, Y. et al., "Large-area shower implanter for thin-film transistors", IEE Proceedings-G Circuits, Devices and Systems, Institution of Electrical Engineers, vol. 141, No. 1, Feb. 1, 1994, pp. 23-36.
Xu et al., "Etching of Nanopatterns in Silicon Using Nanopantography", Applied Physics Letters, vol. 92, Jan. 9, 2008, pp. 1-3.
Xu et al., "Nanopantography: A New Method for Massively Parallel Nanopatterning Over Large Areas", Nano Letters, vol. 5, No. 12, Jan. 2005, pp. 2563-2568.
Yankov et al., "Plasma Immersion Ion Implantation for Silicon Processing", Annalen der Physik, vol. 10, Issue: 4, Feb. 2001, pp. 279-298.
Young et al., "High-Efficiency Si Solar Cells by Beam Processing", Applied Physics Letters, vol. 43, Issue: 7, Oct. 1, 1983, pp. 666-668.
Younger et al, "Ion Implantation Processing for High Performance Concentrator Solar Cells and Cell Assemblies," Solar Cells, vol. 6, 1982, pp. 79-86.
Zeng et al., "Steady-State, Direct-Current (DC) Plasma Immersion Ion Implantation (PIII) for Planar Samples", IEEE, Jan. 2000, pp. 515-519.
Zeng et al., "Steady-State Direct-Current Plasma Immersion Ion Implantation Using an Electron Cycoltron Resonance Plasma Source", Thin Solid Films, www.elsevier.com/locate/tsf, vol. 390, Issues: 1-2, Jun. 30, 2001, pp. 145-148.
Office Action in U.S. Appl. No. 13/312,957, dated Dec. 15, 2014.
Office Action in U.S. Appl. No. 13/299,292 dated Nov. 13, 2013.
Office Action in U.S. Appl. No. 13/299,292 dated May 12, 2014.
International Search Report and Written Opinion for PCT/US2011/061274 mailed on Mar. 29, 2012.
International Preliminary Report on Patentability for PCT/US2011/061274 mailed on May 30, 2013.
Extended Search Report in European Patent Application No. 11841747.6, mailed Jul. 24, 2014.
First Office Action in Chinese Patent Application No. 201180060732.4 dated May 11, 2015.
Second Office Action for Chinese Patent Application No. 201180060732.4 dated Jan. 29, 2016.
Taiwan Office Action in Application No. 100141931 mailed on Jan. 7, 2014.
Notice of Allowance in Taiwanese Patent Application No. 100141931 mailed on Oct. 2, 2014.
International Search Report and Written Opinion for PCT/US2013/075869 mailed on Apr. 16, 2014.
International Preliminary Report on Patentability for PCT/US2013/075869 mailed on Mar. 26, 2015.
Office Action issued in Chinese Patent Application No. 201380066749.X dated Apr. 19, 2016.
Office Action in U.S. Appl. No. 12/482,685 mailed on Feb. 28, 2012.
Office Action in U.S. Appl. No. 12/482,685 mailed on Jun. 6, 2012.
Notice of Allowance in U.S. Appl. No. 12/482,685 mailed on Sep. 6, 2012.
Office Action in U.S. Appl. No. 12/482,685 mailed on Jan. 28, 2013.
Office Action in U.S. Appl. No. 12/482,685 mailed on Jun. 25, 2013.
Office Action in U.S. Appl. No. 12/482,685 mailed Nov. 18, 2013.
Notice of Allowance in U.S. Appl. No. 12/482,685 mailed on Dec. 6, 2013.
International Search Report and Written Opinion for PCT/US2009/047090 mailed on Jul. 31, 2009.
International Preliminary Report on Patentability for PCT/US2009/047090 mailed on Dec. 23, 2010.
First Office Action in Chinese Application No. 200980128201.7, mailed on Dec. 5, 2012.
Second Office Action in Chinese Application No. 200980128201.7 mailed on Aug. 23, 2013.
Third Office Action in Chinese Application No. 200980128201.7 mailed on Apr. 9, 2014.
Fourth Office Action in Chinese Application No. 200980128201.7 mailed on Oct. 24, 2014.
Decision of Rejection in Chinese Application No. 200980128201.7 mailed on Mar. 2, 2015.
Board Opinion in Chinese Patent Application No. 200980128201.7 mailed on Dec. 4, 2015.

(56) **References Cited**

OTHER PUBLICATIONS

Japanese Office Action in Application No. 2011-513699 mailed on Jul. 23, 2013.
Decision to Grant in Japanese Application No. 2011-513699 mailed on Mar. 11, 2014.
Examination Report in Singapore Application No. 201009185-8 dated Jul. 26, 2012.
Office Action in U.S. Appl. No. 12/482,947 mailed on Jun. 7, 2012.
Office Action in U.S. Appl. No. 12/482,947 mailed on Nov. 13, 2013.
Notice of Allowance in U.S. Appl. No. 12/482,947 mailed on Jun. 25, 2014.
International Search Report and Written Opinion for PCT/US2009/047094 mailed on Oct. 2, 2009.
International Preliminary Report on Patentability for PCT/US2009/047094 mailed on Dec. 23, 2010.
Extended Search Report in European Application No. 09763656.7, dated Sep. 13, 2013.
Chinese Office Action in Application No. 200980127944.2 mailed on Feb. 16, 2013.
Japanese Office Action in Application No. 2011-513701 mailed on Jan. 7, 2014.
Decision of Rejection in Japanese Office Action in Application No. 2011-513701 mailed on Jun. 10, 2014.
Written Opinion in Singapore Application No. 201009193-2 mailed on Mar. 18, 2013.
Office Action in U.S. Appl. No. 12/482,980 mailed on Aug. 24, 2012.
Office Action in U.S. Appl. No. 12/482,980 mailed on Feb. 27, 2013.
Advisory Action in U.S. Appl. No. 12/482,980 mailed on Apr. 9, 2013.
International Search Report and Written Opinion for PCT/US2009/047102 mailed on Aug. 4, 2009.
International Preliminary Report on Patentability for PCT/US2009/047102 mailed on Dec. 23, 2010.
Chinese Office Action in Application No. 200980127945.7 mailed on Aug. 31, 2012.
Chinese Office Action in Application No. 200980127945.7 mailed on Jul. 25, 2013.
Chinese Office Action in Application No. 200980127945.7 mailed on Jan. 13, 2014.
Board Opinion in Chinese Patent Application No. 200980127945.7 dated Jun. 30, 2015.
Notification of Grant for Chinese Patent Application No. 200980127945.7 dated Jan. 25, 2016.
First Japanese Office Action in Application No. 2011-513705 mailed on Jul. 16, 2013.
Decision for Rejection in Japanese Patent Application No. 2011-513705 mailed on Jan. 7, 2014.
Notice of Reasons for Preliminary Rejection for Korean Patent Application No. 10-2011-7000467 dated Jul. 26, 2015.
Written Opinion in Singapore Patent Application No. 201009191-6 dated Jul. 11, 2012.
2nd Written Opinion in Singapore Patent Application No. 201009191-6 dated Jun. 14, 2013.
Examination Report in Singapore Patent Application No. 201009191-6 dated Feb. 11, 2014.
Office Action in U.S. Appl. No. 12/483,017 mailed on Sep. 25, 2012.
Office Action in U.S. Appl. No. 12/483,017 mailed on Apr. 23, 2013.
Office Action in U.S. Appl. No. 12/483,017 mailed on Oct. 4, 2013.
International Search Report and Written Opinion for PCT/US2009/047109 mailed on Jul. 29, 2009.
International Preliminary Report on Patentability for PCT/US2009/047109 mailed on Dec. 23, 2010.
Chinese Office Action in Application No. 200980128202.1, mailed on May 8, 2013.
Japanese Office Action in Application No. 2011-513706, mailed on Jul. 30, 2013.
Second Office Action in Japanese Application No. 2011-513706, mailed on Apr. 1, 2014.
Decision for Rejection in Japanese Application No. 2011-513706, mailed on Sep. 2, 2014.
Written Opinion in Singapore Patent Application No. 201009194-0 dated Jul. 11, 2012.
Examination Report in Singapore Application No. 201009194-0 dated Jun. 25, 2013.
Office Action in U.S. Appl. No. 12/728,105 mailed on Jan. 14, 2013.
Office Action in U.S. Appl. No. 12/728,105 mailed on May 21, 2013.
International Search Report and Written Opinion for PCT/US2010/028058 mailed on May 25, 2010.
International Preliminary Report on Patentability for PCT/US2010/028058 mailed on Sep. 29, 2011.
Chinese Office Action in Application No. 201080012752.X mailed on Aug. 8, 2013.
Second Chinese Office Action in Application No. 201080012752.X mailed on Jan. 8, 2014.
Japanese Office Action in Application No. 2012-501017 mailed Nov. 26, 2013.
Decision for Rejection in Japanese Patent Application No. 2012-501017 mailed on Apr. 22, 2014.
Office Action in Korean Patent Application No. 10-2011-7024287 dated May 16, 2016, with English translation (21 pgs).
Written Opinion in Singapore Patent Application No. 201106457-3 dated Jun. 5, 2012.
Examination Report in Singapore Patent Application No. 201106457-3 dated Jan. 18, 2013.
Office Action in U.S. Appl. No. 12/821,053 mailed on Mar. 15, 2012.
Office Action in U.S. Appl. No. 12/821,053 mailed on Aug. 17, 2012.
Office Action in U.S. Appl. No. 12/821,053 mailed on Jan. 16, 2013.
Office Action in U.S. Appl. No. 12/821,053 mailed on Aug. 13, 2013.
Advisory Action in U.S. Appl. No. 12/821,053 mailed on Jan. 9, 2014.
Notice of Allowance in U.S. Appl. No. 12/821,053 mailed on Feb. 27, 2014.
International Search Report and Written Opinion in International Application No. PCT/US10/39690 dated Oct. 7, 2010.
International Preliminary Report on Patentability for PCT/US10/39690 mailed on Jan. 12, 2012.
Extended Search Report in European Patent Application No. 10797606.0, dated Jun. 18, 2015.
First Office Action and Examination Report in Chinese Patent Application No. 201180018217.X, dated Nov. 3, 2014.
Second Office Action in Chinese Patent Application No. 201180018217.X, dated Jun. 9, 2015.
Office Action in Chinese Patent Application No. 201180018217.X dated Oct. 19, 2015.
Notice of Grant for Chinese Patent Application No. 201180018217.X dated Jan. 29, 2016.
Office Action in U.S. Appl. No. 13/871,871 dated Jan. 21, 2016.
Extended Search Report in European Patent Application No. 14176404.3, dated Nov. 14, 2014.
Office Action in U.S. Appl. No. 14/135,519 dated Jul. 9, 2015.
Notice of Allowance in U.S. Appl. No. 14/135,519 dated Nov. 18, 2015.
International Search Report and Written Opinion for PCT/US2013/076741, mailed on Apr. 18, 2014.
International Preliminary Report on Patentability for PCT/US2013/076741, mailed on Jul. 2, 2015.
First Office Action and Examination Report in Taiwanese Patent Application No. 102147302, dated Apr. 8, 2015.
Office Action in U.S. Appl. No. 15/073,427 dated May 20, 2016.
Office Action in Taiwanese Patent Application No. 102147302, dated Jul. 22, 2015.
Board Decision in Chinese Patent Application No. 200980127945.7 dated Dec. 29, 2015. Rejection Reversed.
Examination Report for Taiwanese Patent Application No. 101141546 dated Sep. 16, 2014.

(56) **References Cited**

OTHER PUBLICATIONS

Examination Report in Singapore Patent Application No. 11201402177X dated Aug. 18, 2015.
Office Action in U.S. Appl. No. 13/719,145 dated Sep. 17, 2015.
First Office Action for Chinese Patent Application No. 201280061122.0 dated Apr. 29, 2016.
International Preliminary Report on Patentability PCT/US2012/064241 mailed on May 22, 2014.
International Search Report and Written Opinion in International Application No. PCT/US2012/064241 mailed on Mar. 26, 2013.
Notice of Allowance in U.S. Appl. No. 13/672,652 dated Dec. 22, 2015.
Office Action in U.S. Appl. No. 13/672,652, mailed on Feb. 17, 2015.
Office Action in U.S. Appl. No. 13/719,145, mailed on Mar. 30, 2015.
Office Action in U.S. Appl. No. 13/672,652 dated Sep. 10, 2015.
Office Action in U.S. Appl. No. 13/719,145 dated Jan. 12, 2016.
Restriction Requirement in U.S. Appl. No. 12/482,685 dated Feb. 1, 2012.
Restriction Requirement in U.S. Appl. No. 12/482,980 dated Apr. 24, 2012.
Restriction Requirement in U.S. Appl. No. 12/483,017 dated Apr. 25, 2012.
Restriction Requirement in U.S. Appl. No. 12/728,105 dated Oct. 5, 2012.
Restriction Requirement in U.S. Appl. No. 13/024,251 mailed on Jun. 19, 2013.
Restriction Requirement in U.S. Appl. No. 13/299,292 dated Aug. 13, 2013.
Restriction Requirement in U.S. Appl. No. 13/363,347, mailed on Jul. 9, 2013.
Restriction Requirement in U.S. Appl. No. 13/672,652, mailed on Aug. 8, 2014.
Restriction Requirement in U.S. Appl. No. 13/719,145, mailed on Dec. 10, 2014.
Second Board Opinion for Chinese Patent Application No. 200980128201.7 dated Jun. 1, 2016.
Third Office Action for Chinese Patent Application No. 201180060732.4 dated Jun. 20, 2016.
Written Opinion in Singapore Patent Application No. 11201402177X, mailed on Mar. 11, 2015.
Notice of Allowance in U.S. Appl. No. 15/073,427 dated Sep. 23, 2016.
Search Report and Written Opinion in Singapore Patent Application No. 10201500916V, mailed on Aug. 5, 2016.
Office Action in U.S. Appl. No. 13/719,145 dated Oct. 19, 2016.
Second Office Action for Chinese Patent Application No. 201380066749.X dated Dec. 9, 2016.
Extended Search Report in European Patent Application No. 12847303.0, dated Dec. 16, 2014.
Examination Report in European Patent Application No. 12847303.0 dated Dec. 7, 2016.
Notice of Grant for Chinese Patent Application No. 201280061122.0 dated Nov. 3, 2016.
Notice of Grant for Japanese Patent Application No. 2014-541275 dated Nov. 22, 2016.
Examination Report for Taiwanese Patent Application No. 101141546 dated Mar. 25, 2015.
Office Action for U.S. Appl. No. 15/099,523 dated Dec. 14, 2016.
Office Action for Korean Patent Application No. 10-2012-7023526 dated Dec. 22, 2016.

* cited by examiner

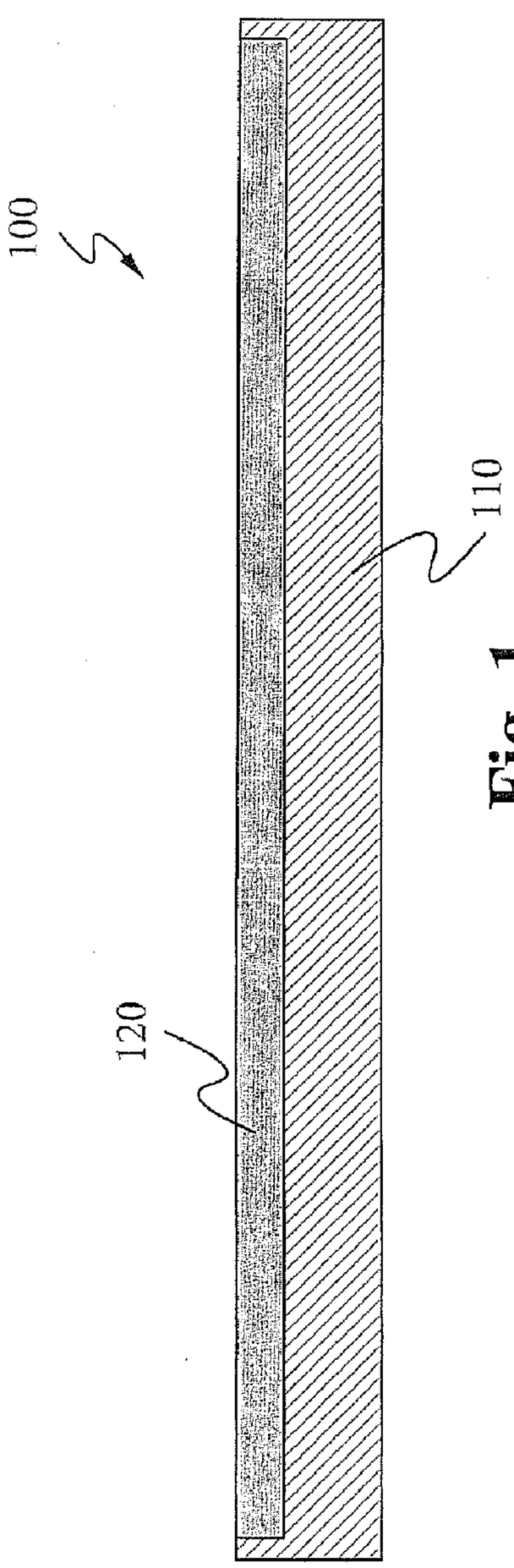


Fig. 1

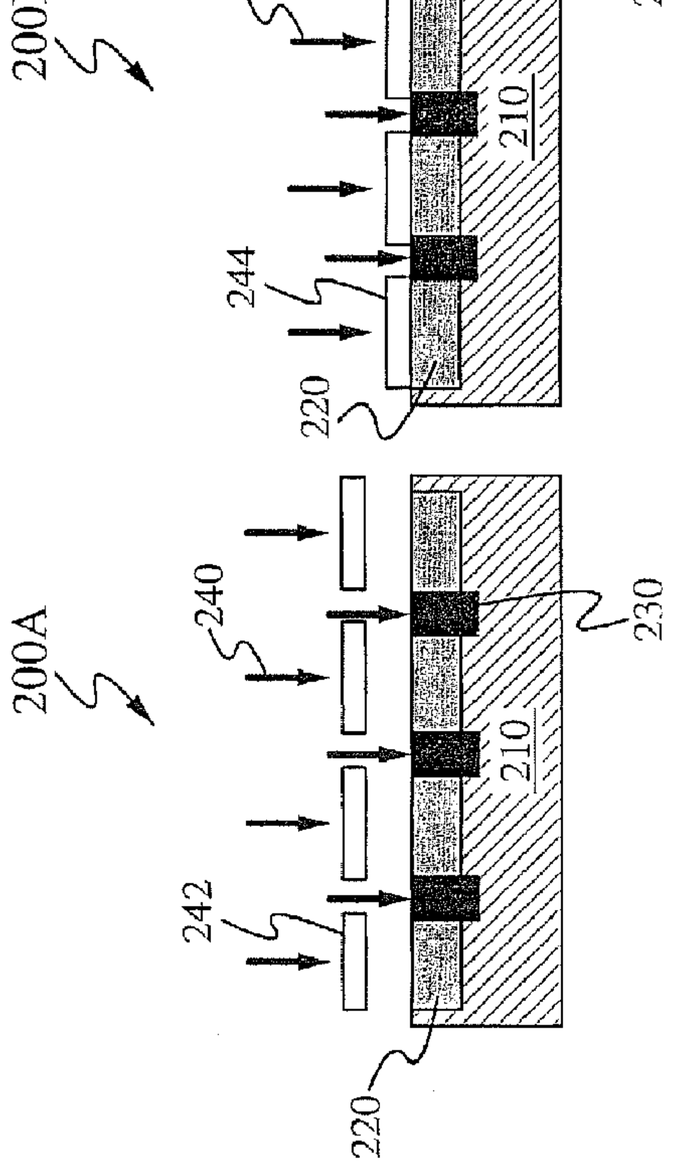


Fig. 2B

Fig. 2A

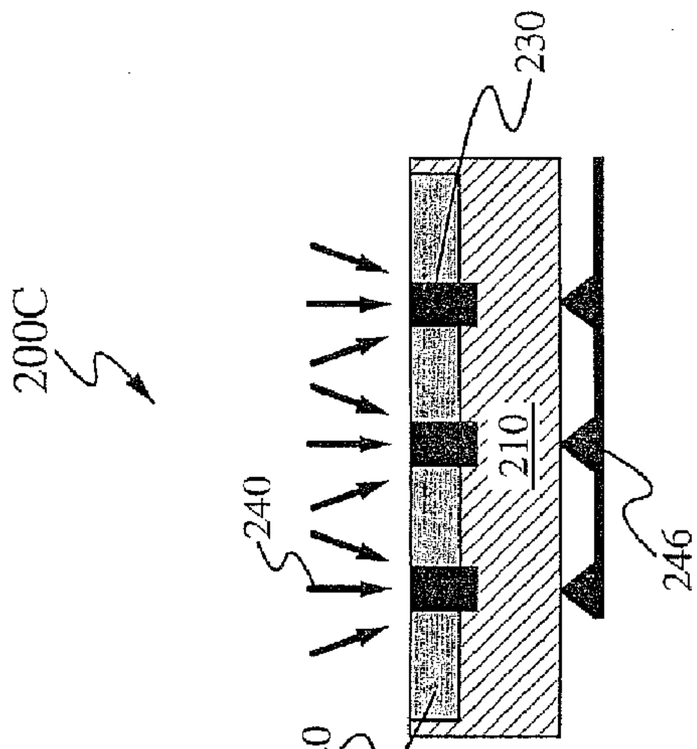


Fig. 2C

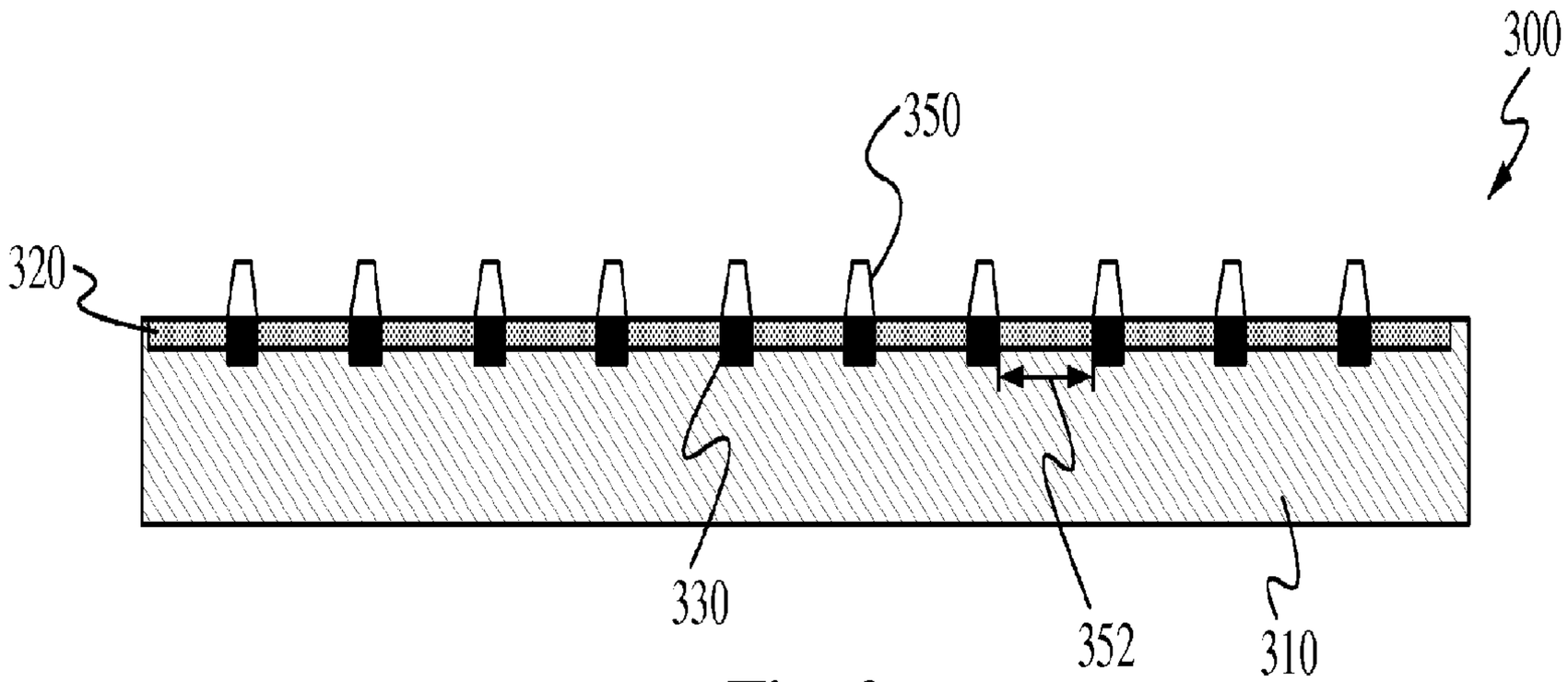

300
350
320
330
352
310

Fig. 3

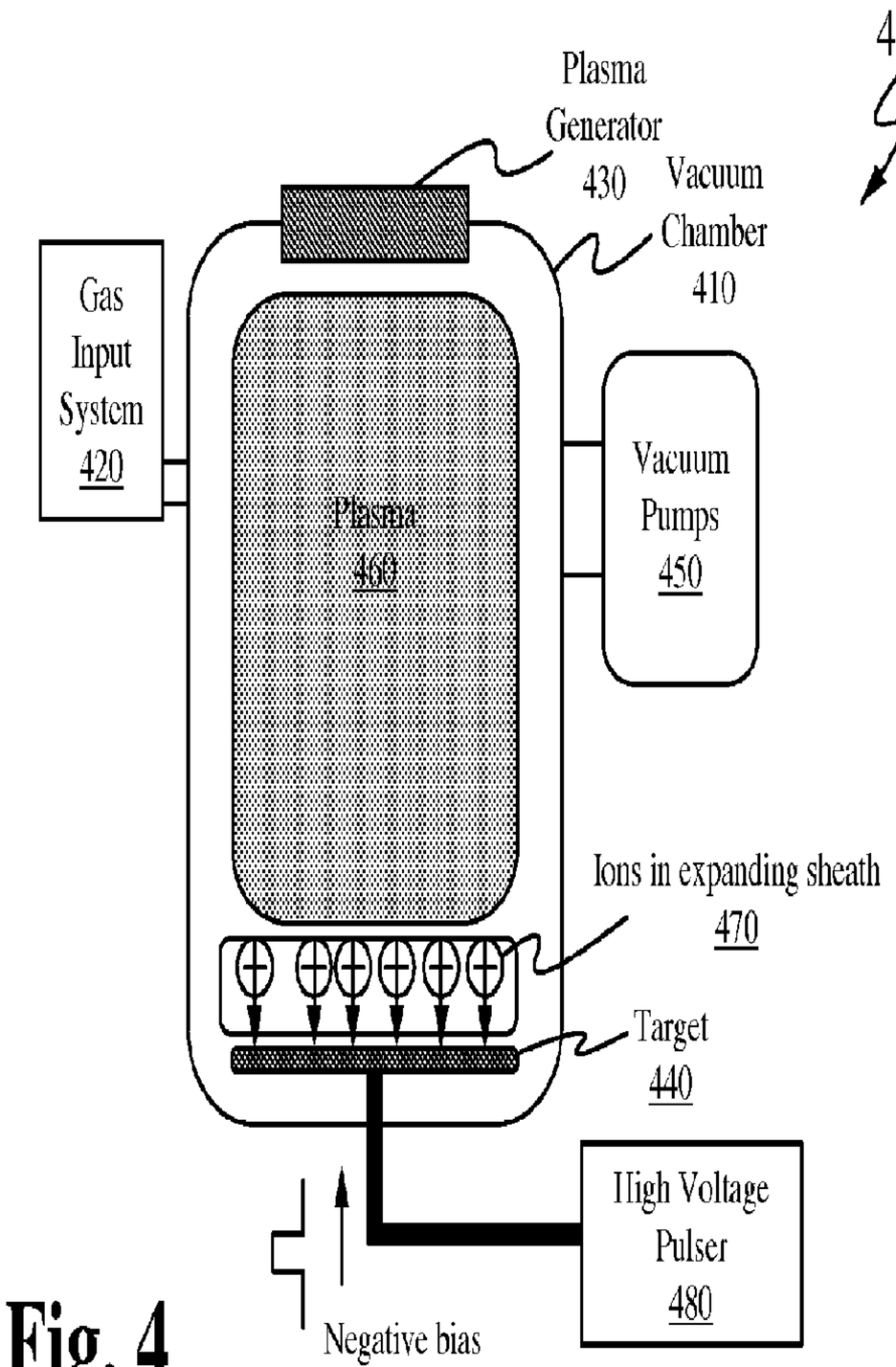

400
Plasma Generator 430
Vacuum Chamber 410
Gas Input System 420
Plasma 460
Vacuum Pumps 450
Ions in expanding sheath 470
Target 440
High Voltage Pulser 480
Negative bias

Fig. 4

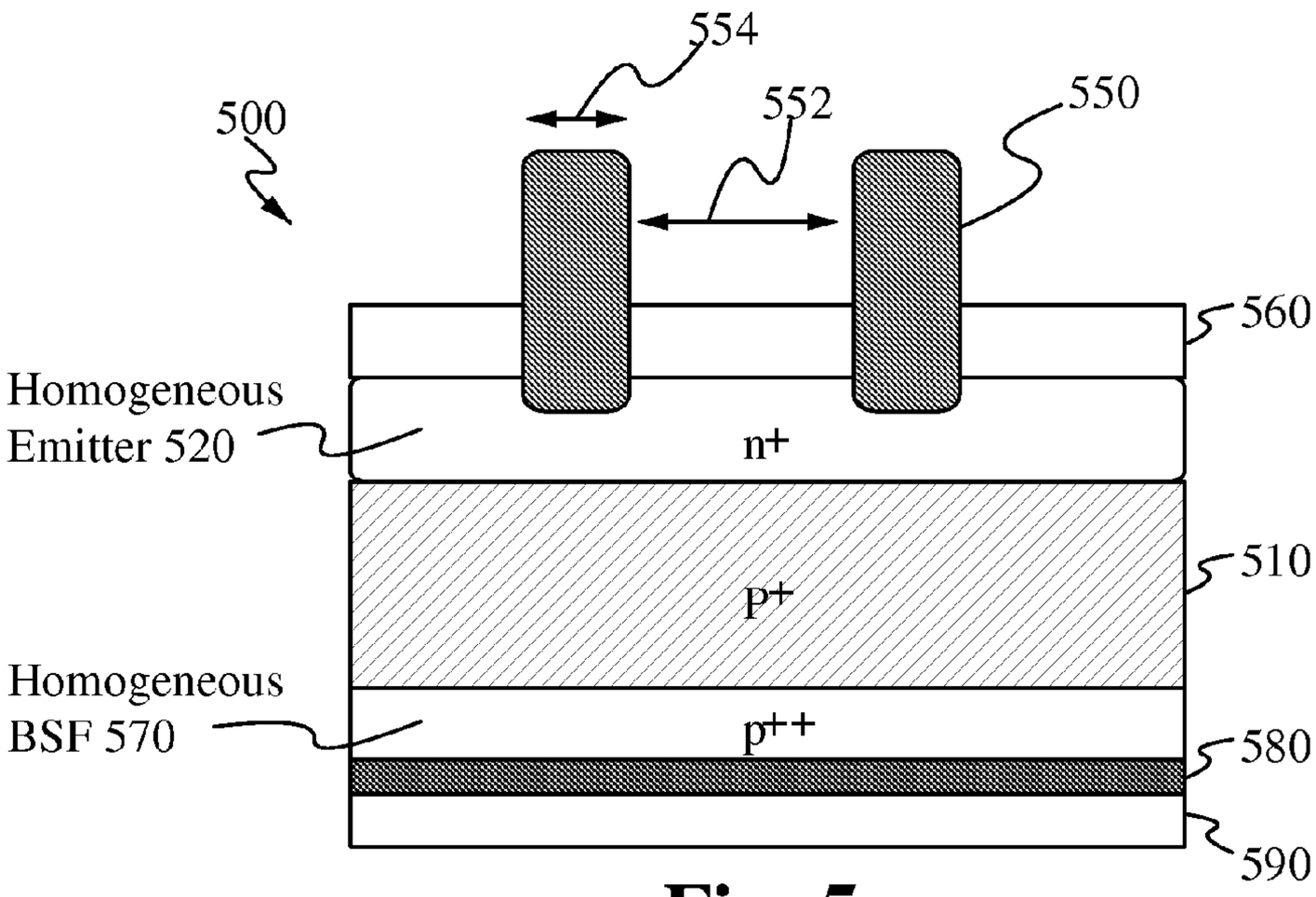

554
552
550
500
560
Homogeneous
Emitter 520
n+
p+
510
Homogeneous
BSF 570
p++
580
590

Fig. 5

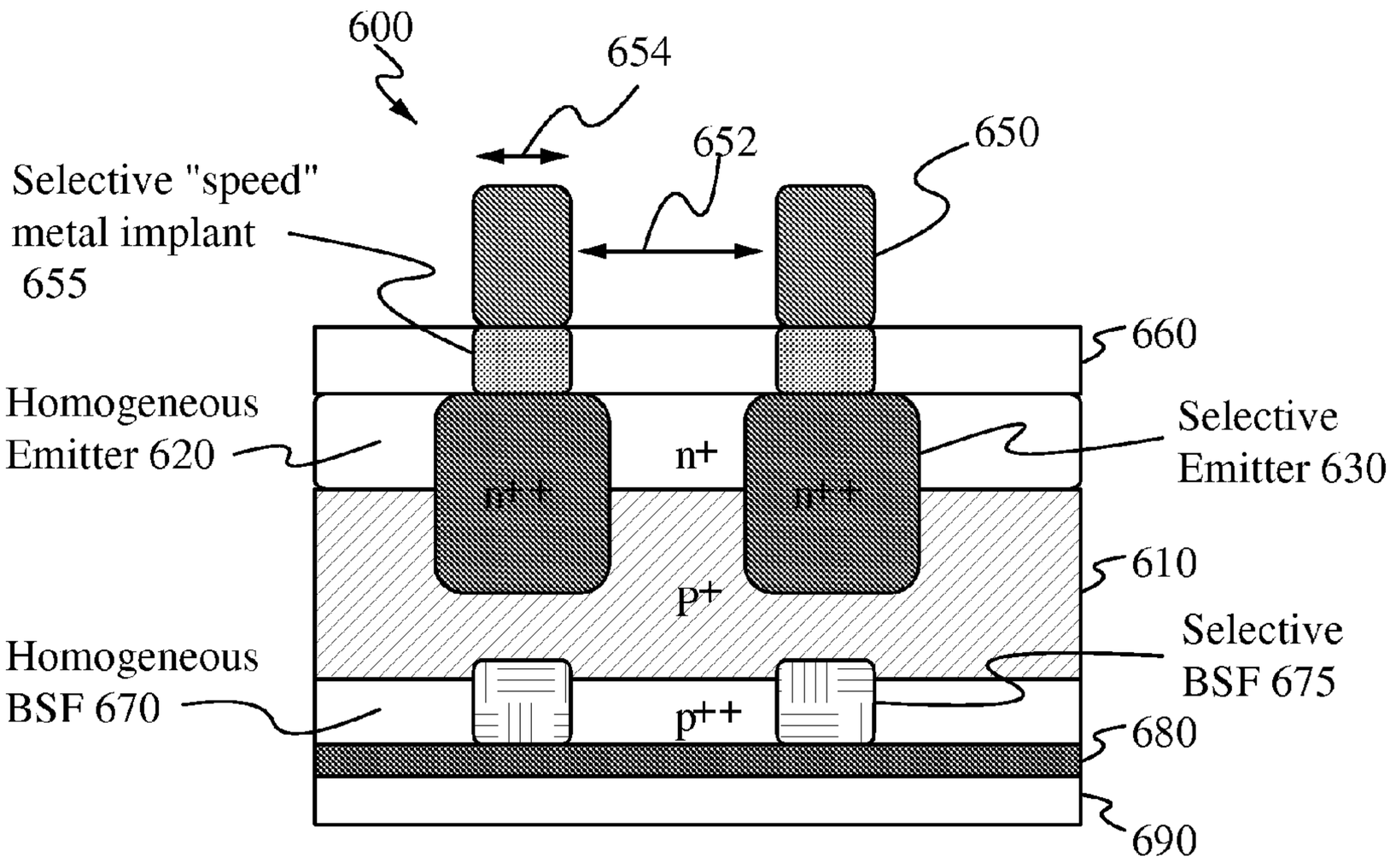

600
654
652
650
Selective "speed"
metal implant
655
660
Homogeneous
Emitter 620
n+
n++
n++
Selective
Emitter 630
610
p+
Selective
BSF 675
Homogeneous
BSF 670
p++
680
690

Fig. 6

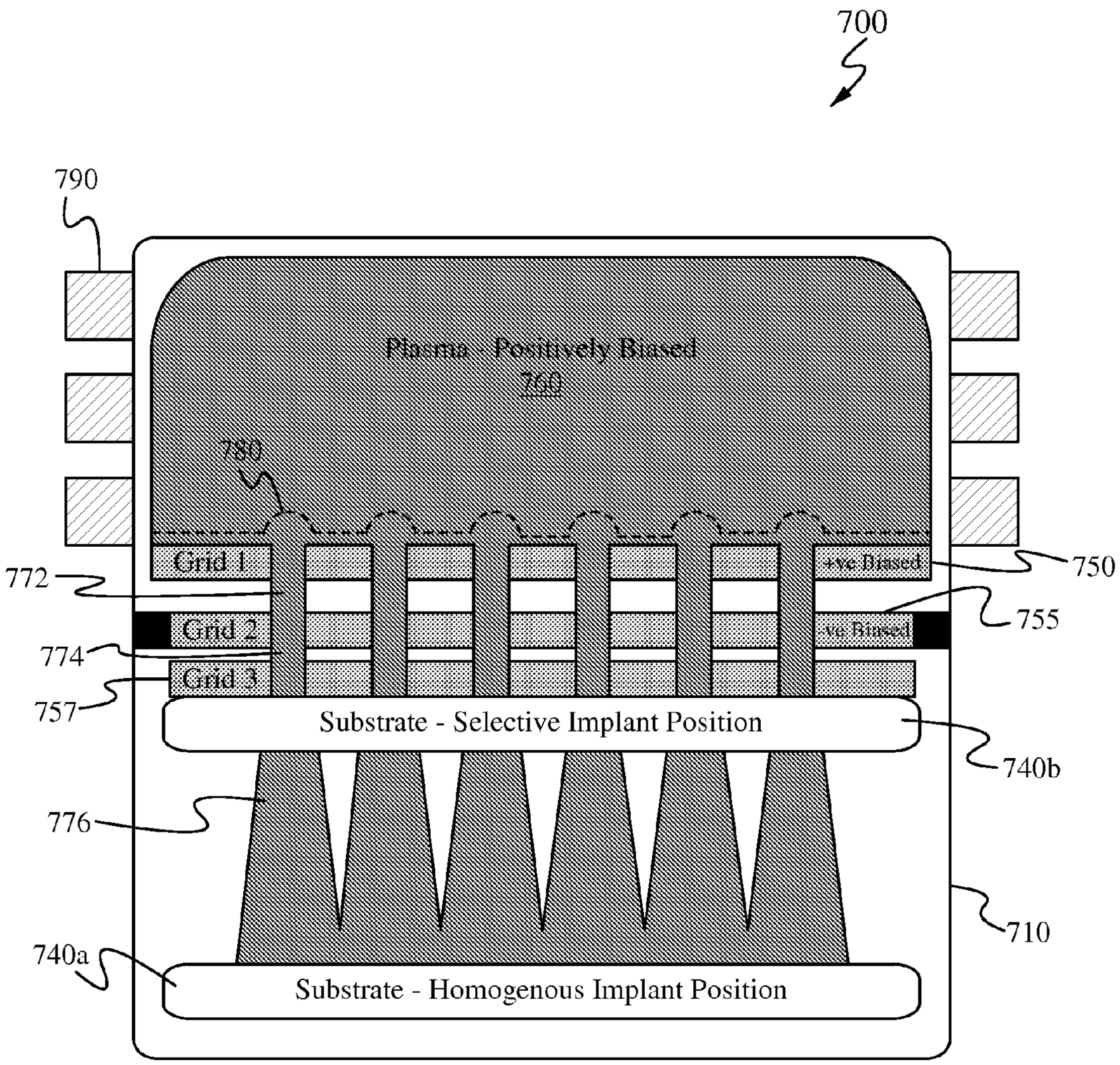

700
790
Plasma - Positively Biased
760
780
Grid 1
+ve Biased
750
772
Grid 2
-ve Biased
755
774
Grid 3
757
Substrate - Selective Implant Position
740b
776
710
740a
Substrate - Homogenous Implant Position

Fig. 7

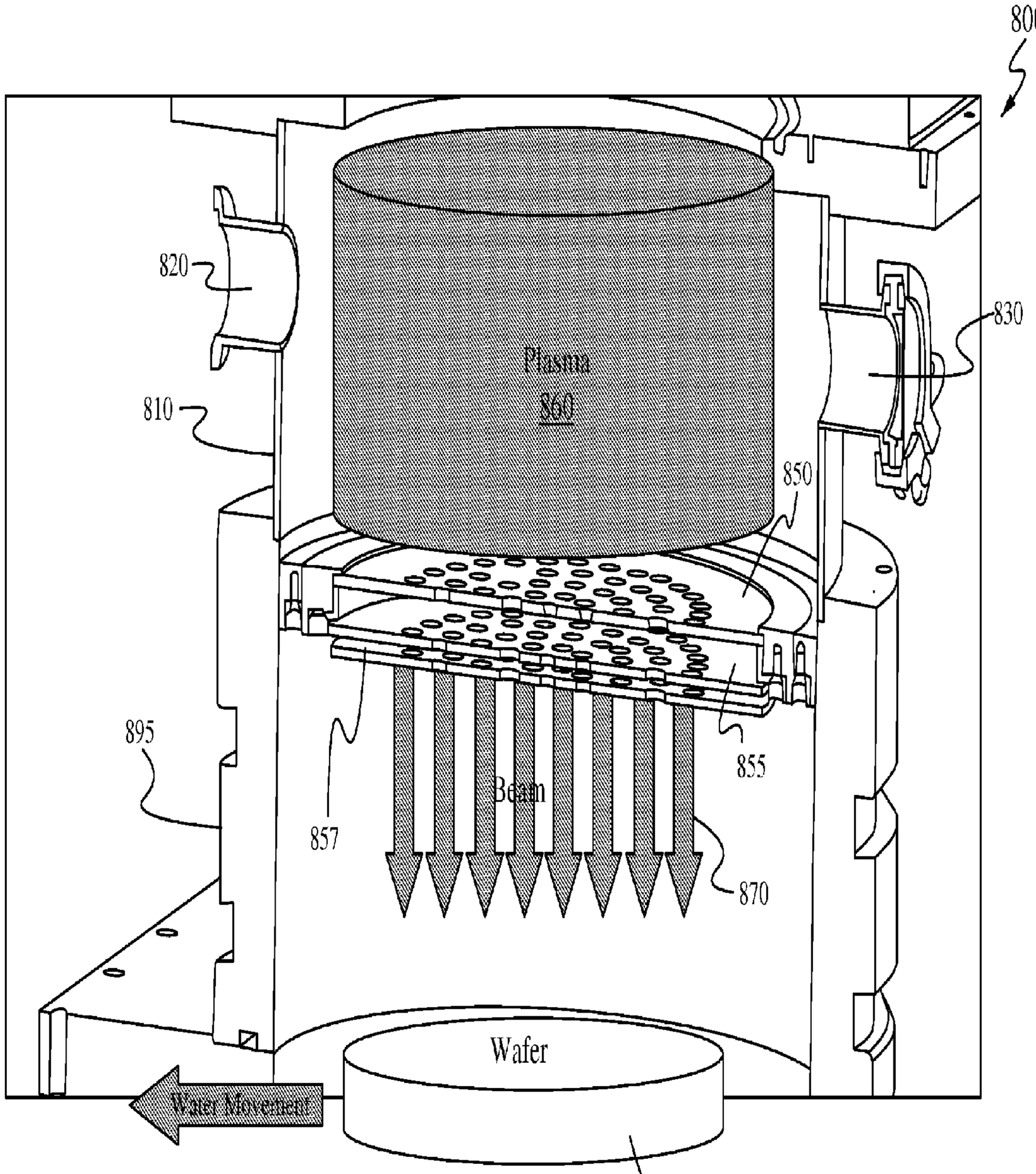

800
820
830
Plasma
860
810
850
895
855
857
Beam
870
Wafer
Wafer Movement
840

Fig. 8

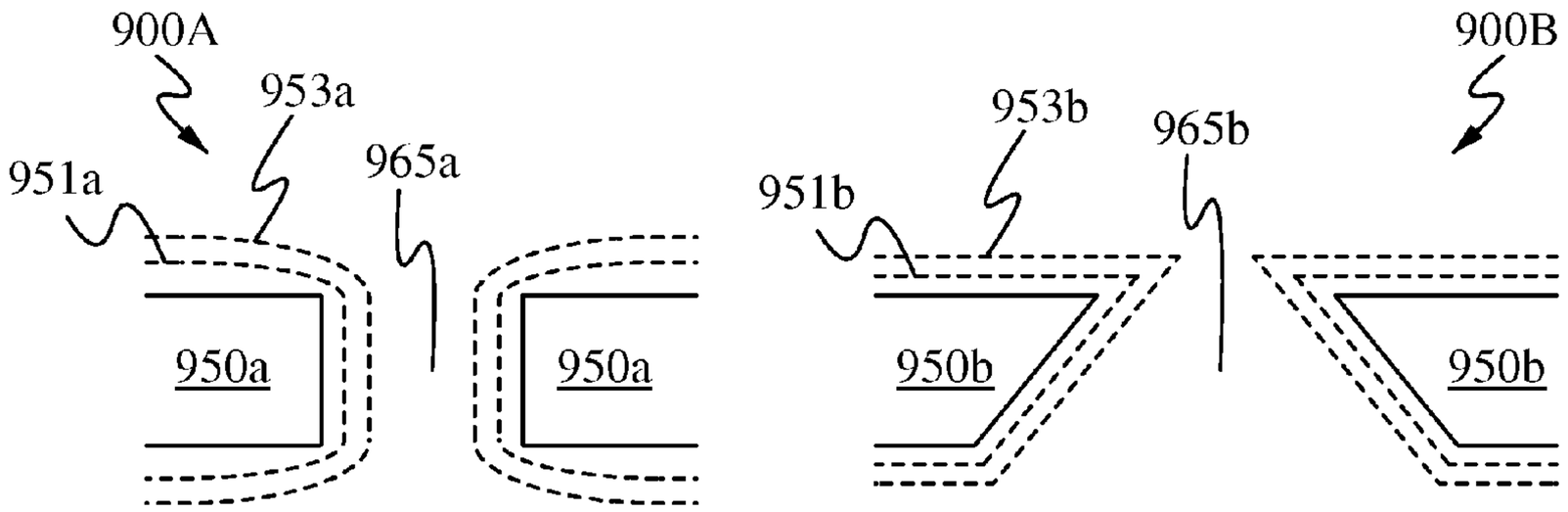


Fig. 9A Fig. 9B

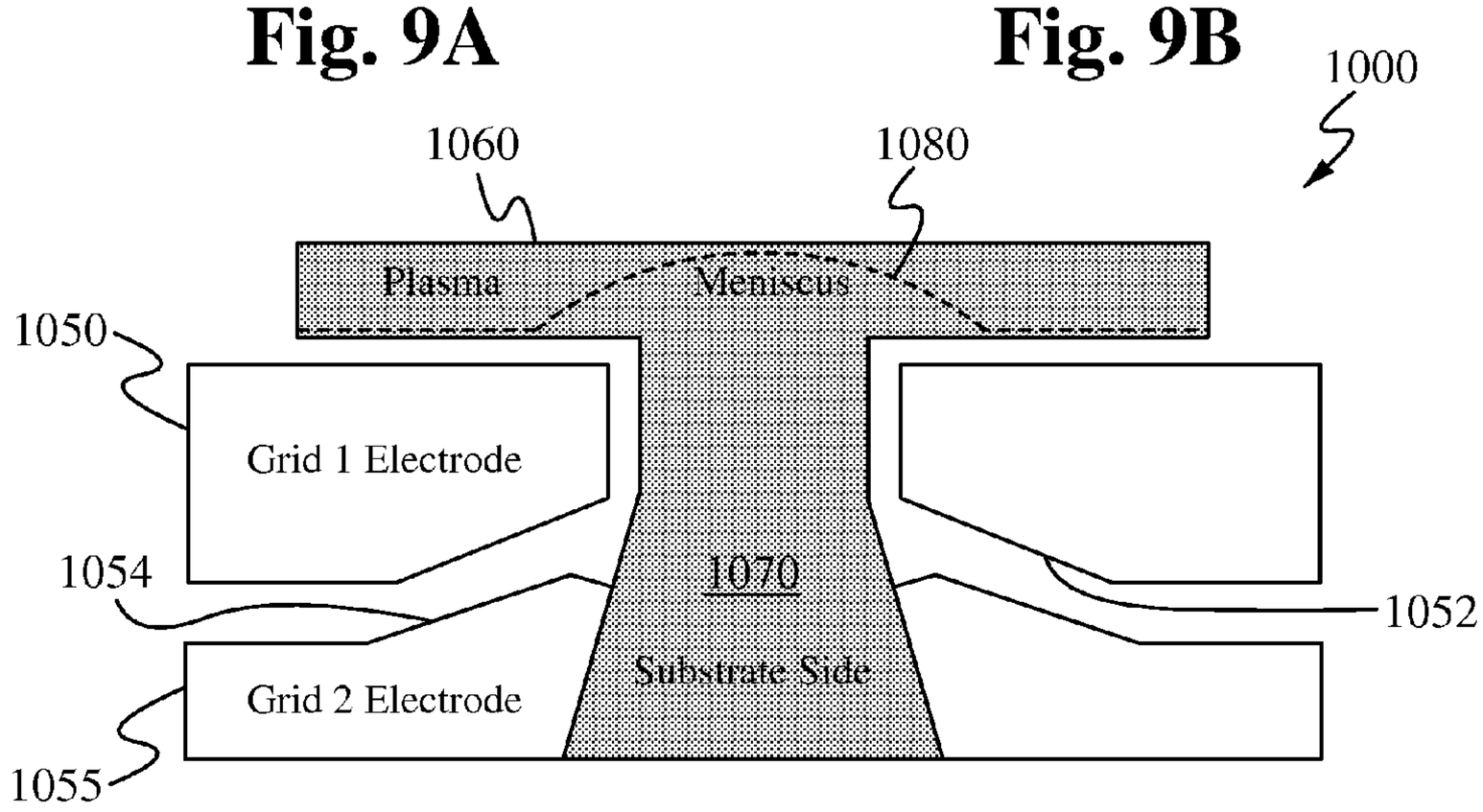


Fig. 10

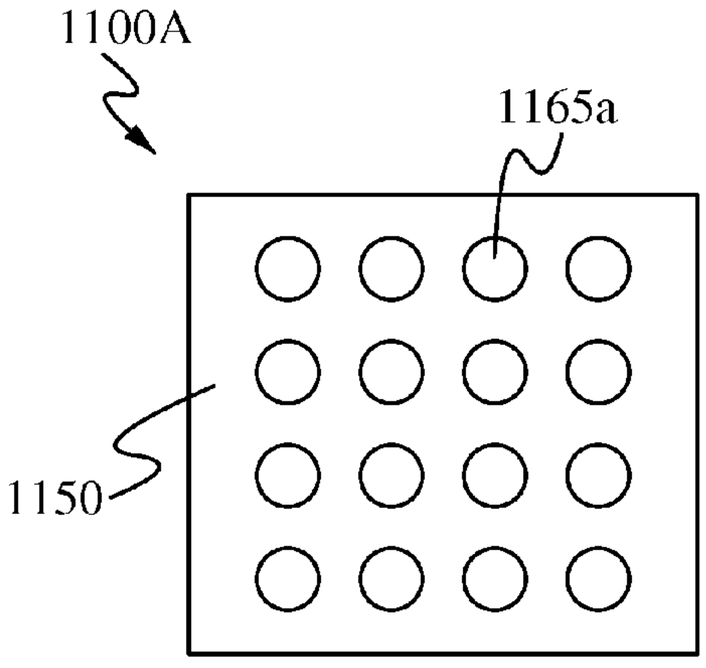


Fig. 11A

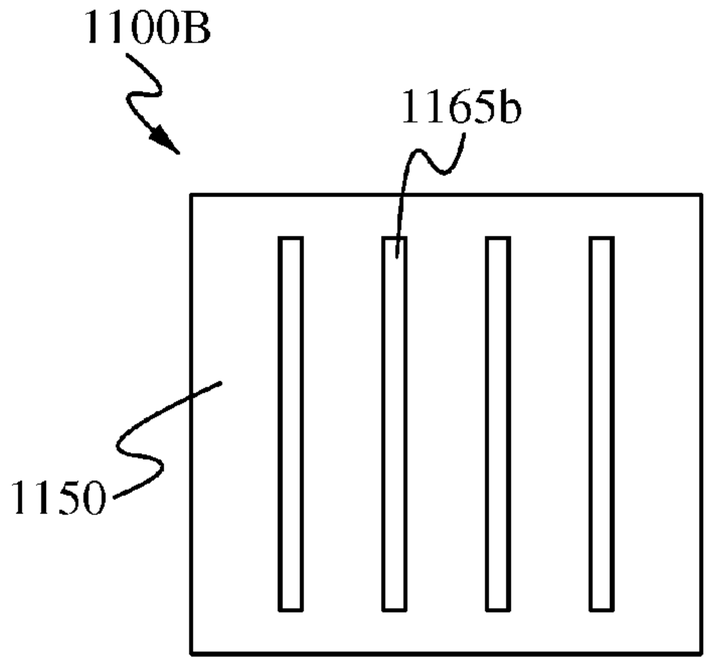


Fig. 11B

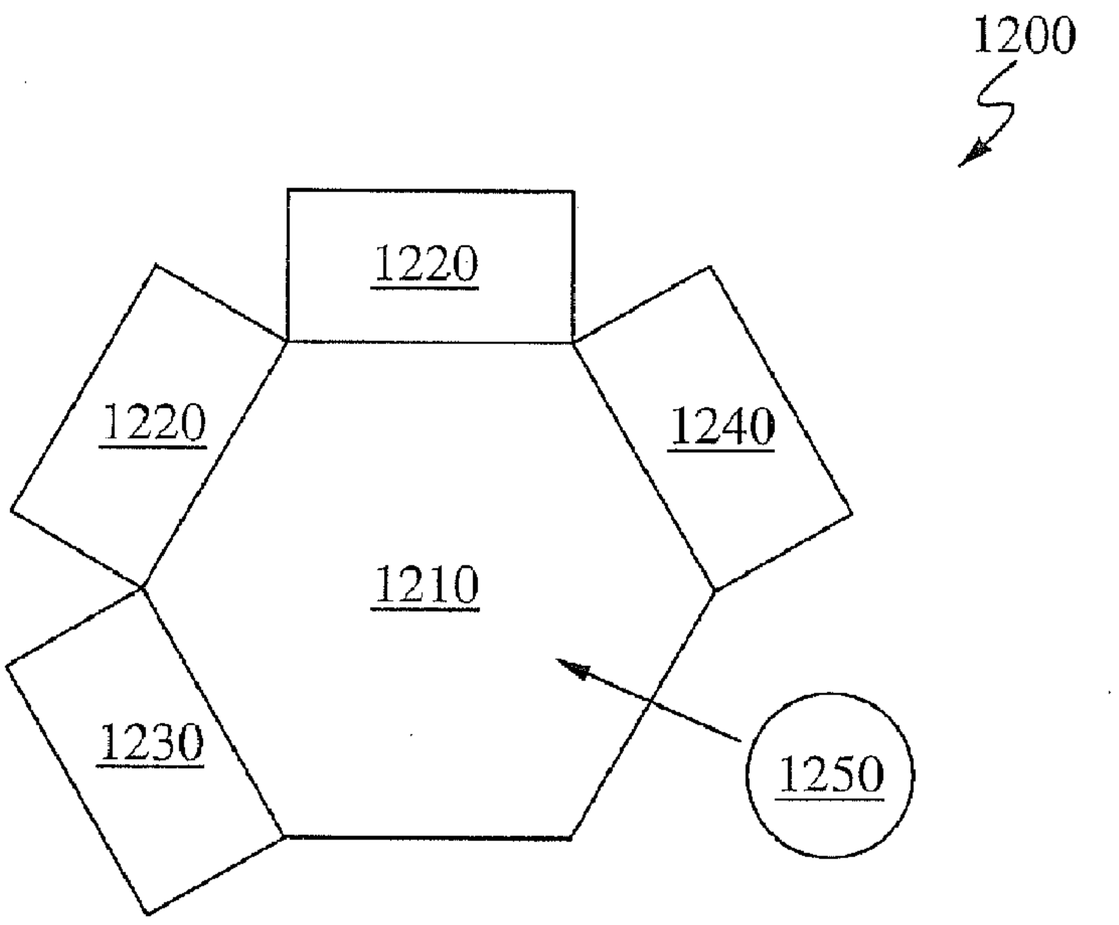

1200
1220
1220
1240
1210
1230
1250

Fig. 12

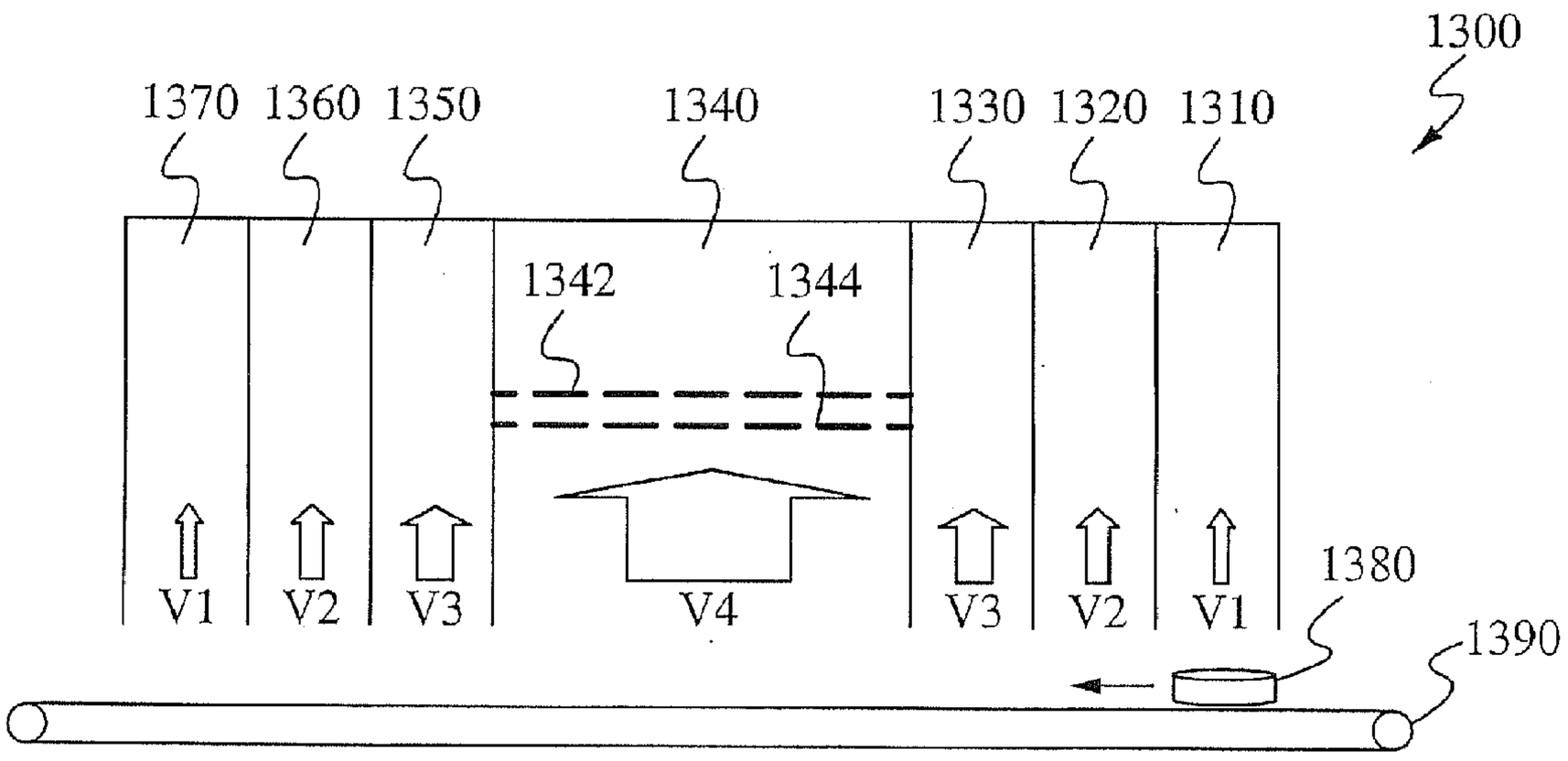

1300
1370 1360 1350 1340 1330 1320 1310
1342 1344
V1 V2 V3 V4 V3 V2 V1
1380
1390

Fig. 13

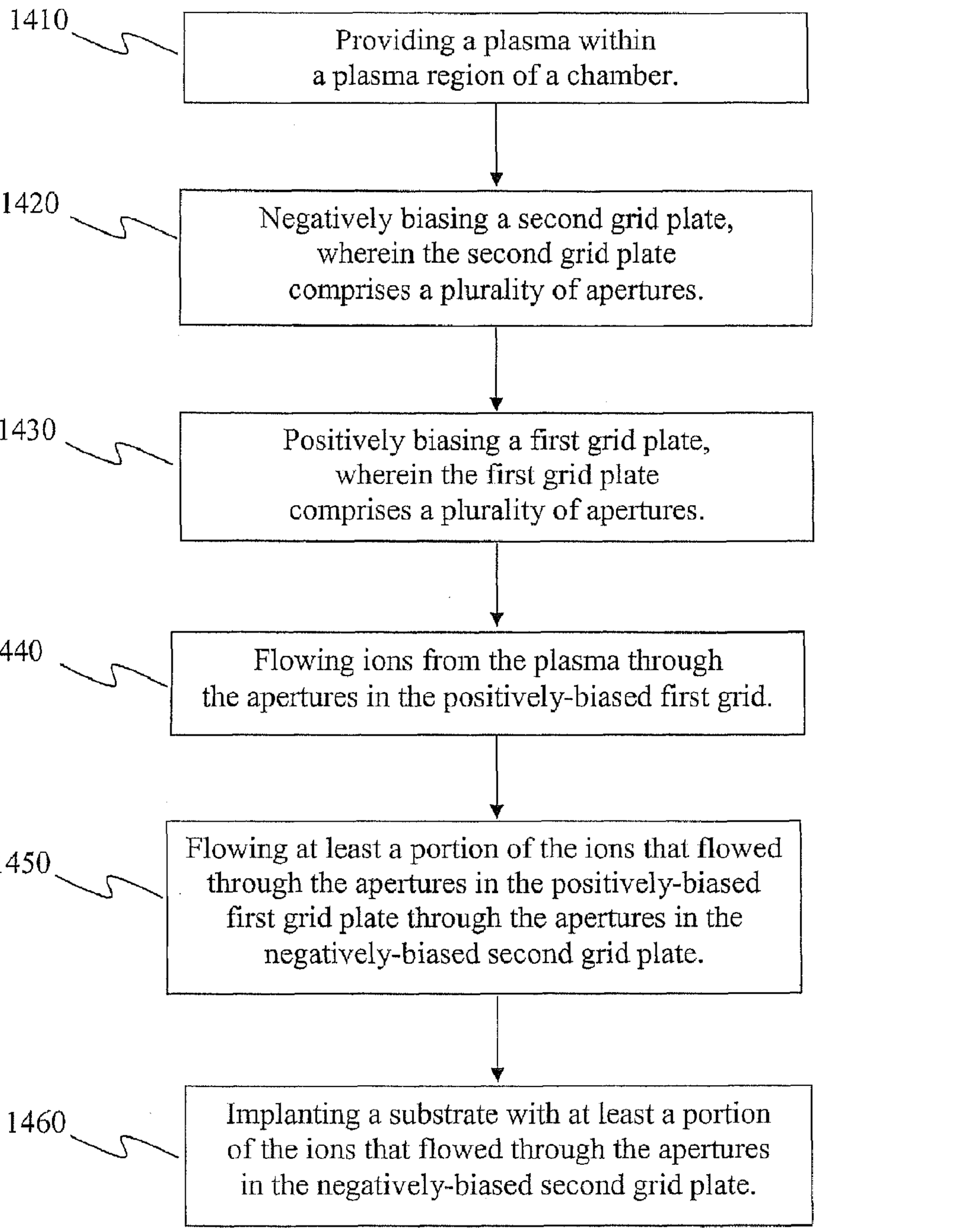

1400
1410
Providing a plasma within a plasma region of a chamber.
1420
Negatively biasing a second grid plate, wherein the second grid plate comprises a plurality of apertures.
1430
Positively biasing a first grid plate, wherein the first grid plate comprises a plurality of apertures.
1440
Flowing ions from the plasma through the apertures in the positively-biased first grid.
1450
Flowing at least a portion of the ions that flowed through the apertures in the positively-biased first grid plate through the apertures in the negatively-biased second grid plate.
1460
Implanting a substrate with at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate.

FIG. 14

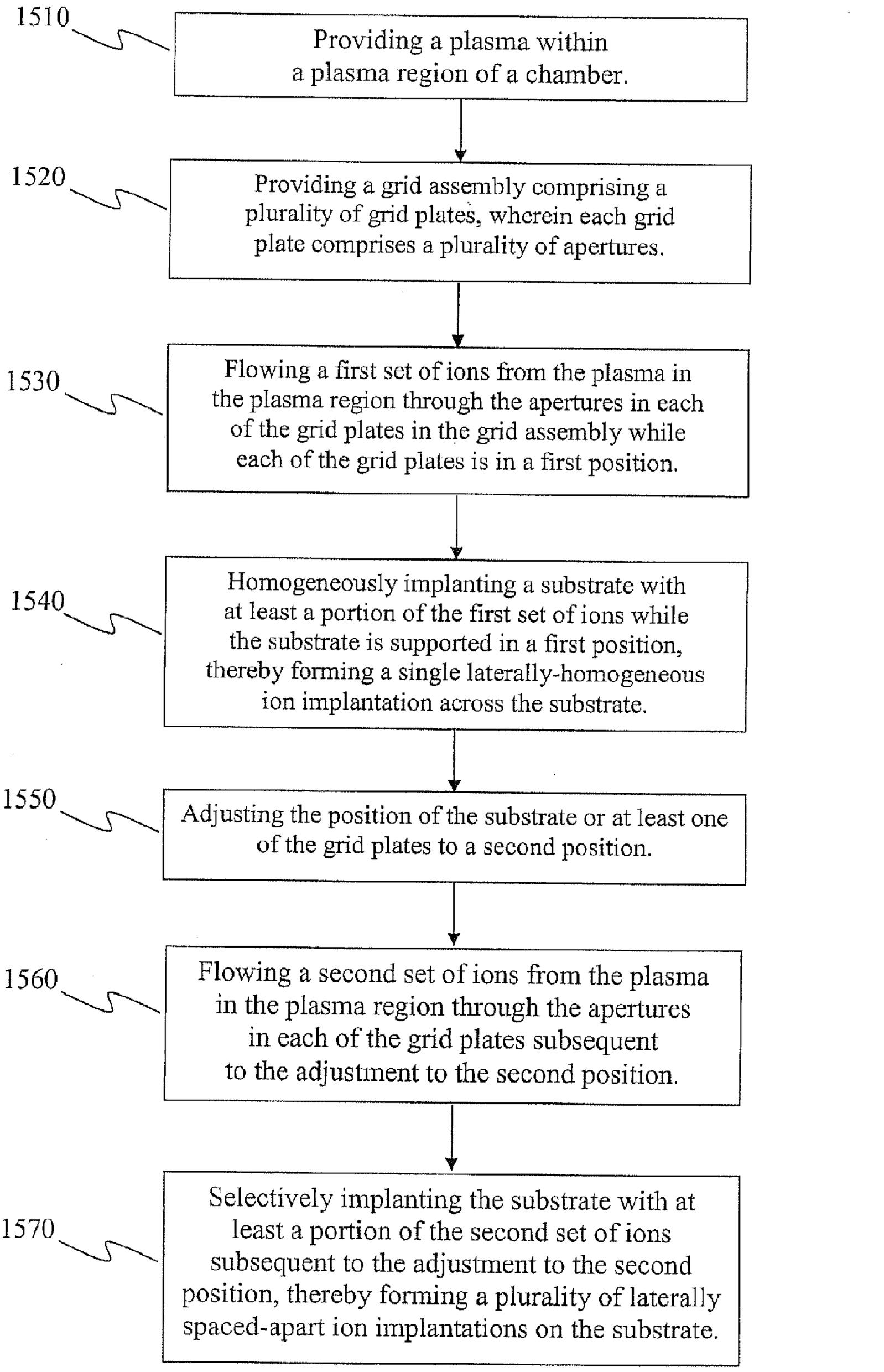

1500
1510
Providing a plasma within a plasma region of a chamber.
1520
Providing a grid assembly comprising a plurality of grid plates, wherein each grid plate comprises a plurality of apertures.
1530
Flowing a first set of ions from the plasma in the plasma region through the apertures in each of the grid plates in the grid assembly while each of the grid plates is in a first position.
1540
Homogeneously implanting a substrate with at least a portion of the first set of ions while the substrate is supported in a first position, thereby forming a single laterally-homogeneous ion implantation across the substrate.
1550
Adjusting the position of the substrate or at least one of the grid plates to a second position.
1560
Flowing a second set of ions from the plasma in the plasma region through the apertures in each of the grid plates subsequent to the adjustment to the second position.
1570
Selectively implanting the substrate with at least a portion of the second set of ions subsequent to the adjustment to the second position, thereby forming a plurality of laterally spaced-apart ion implantations on the substrate.

FIG. 15

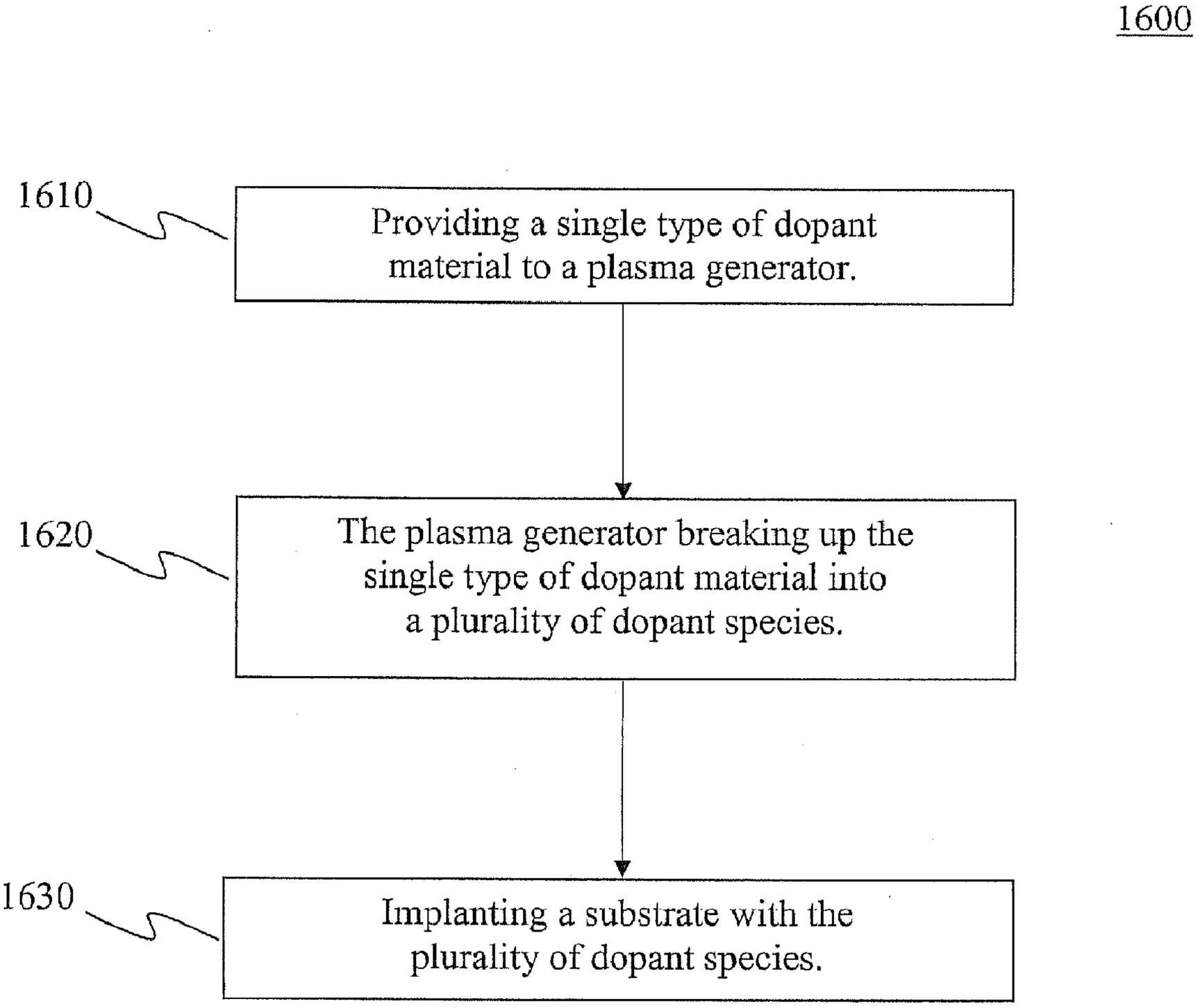

1600
1610
Providing a single type of dopant material to a plasma generator.
1620
The plasma generator breaking up the single type of dopant material into a plurality of dopant species.
1630
Implanting a substrate with the plurality of dopant species.

FIG. 16

ION IMPLANT SYSTEM HAVING GRID ASSEMBLY

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a divisional application of U.S. patent application Ser. No. 14/510,109, filed on Oct. 8, 2014, which is a divisional application of U.S. patent application Ser. No. 13/363,341, filed on Jan. 31, 2012 (now U.S. Pat. No. 8,997,688), which is a divisional application of U.S. patent application Ser. No. 12/821,053, filed on Jun. 22, 2010 (now U.S. Pat. No. 8,749,053), and which claims priority from U.S. Provisional Application No. 61/219,379, filed Jun. 23, 2009, the disclosures of which are incorporated herein in their entireties.

FIELD OF THE INVENTION

The present invention relates generally to the field of solar cells and other large substrate implant applications. More particularly, the present invention relates to solar cell devices and methods of their formation.

BACKGROUND OF THE INVENTION

Although traditional beamline implantation of wafers can provide high power density, it has several disadvantages. For example, it only provides a single beamlet. Additionally, it uses a lot of power in a small beam spot, and the wafer gets quite hot. As a result, productivity is low.

SUMMARY OF THE INVENTION

In one aspect of the present invention, a plasma grid implantation system is provided. The system comprises: a plasma source configured to provide plasma; a first grid plate comprising a plurality of apertures configured to allow ions from the plasma in a plasma region to pass therethrough, wherein the first grid plate is configured to be positively biased, either continuously in DC mode or in pulsed mode, by a power supply; a second grid plate comprising a plurality of apertures configured to allow the ions to pass therethrough subsequent to the ions passing through the first grid plate, wherein the second grid plate is configured to be negatively biased, either continuously in DC mode or in pulsed mode, by a power supply; and a substrate holder configured to support a substrate in a position where the substrate is implanted with the ions subsequent to the ions passing through the second grid plate.

In some embodiments, the position of at least one of the first grid plate, the second grid plate, and the substrate holder is configured to be adjusted between a homogeneous implantation position and a selective implantation position, the homogeneous implantation position is configured to enable a single laterally-homogeneous ion implantation across the substrate on the substrate holder, wherein the single laterally-homogeneous ion implantation is formed from a combination of ions that have passed through different apertures of the second grid plate, and the selective implantation position is configured to enable a plurality of laterally spaced-apart ion implantations of the substrate on the substrate holder, wherein the plurality of laterally spaced-apart ion implantations is formed from ions that have passed through the different apertures of the second grid plate.

In some embodiments, the system further comprises a third grid plate disposed between the second grid plate and the substrate holder, and the third grid plate comprises a plurality of apertures configured to allow the ions to pass therethrough subsequent to the ions passing through the second grid plate. In some embodiments, the third grid plate is grounded. In some embodiments, the position of at least one of the third grid plate and the substrate holder is configured to be adjusted between a homogeneous implantation position and a selective implantation position, the homogeneous implantation position configured to enable a single laterally-homogeneous ion implantation across the substrate on the substrate holder, wherein the single laterally-homogeneous ion implantation is formed from a combination of ions that have passed through different apertures of the second grid plate, and the selective implantation position configured to enable a plurality of laterally spaced-apart ion implantations of the substrate on the substrate holder, wherein the plurality of laterally spaced-apart ion implantations is formed from ions that have passed through the different apertures of the second grid plate.

In some embodiments, the apertures of at least one of the first grid plate and the second grid plate are substantially circular holes. In some embodiments, the apertures of at least one of the first grid plate and the second grid plate are elongated slots. In some embodiments, each one of the apertures of at least one of the first grid plate and the second grid plate comprises a top end and a bottom end, wherein the bottom end is closer to the substrate holder than the top end, and wherein the diameter of each aperture gradually increases from the top end to the bottom end.

In some embodiments, the first grid plate and the second grid plate comprise a material chosen from the group consisting of: silicon, graphite, silicon carbide, and tungsten. In some embodiments, the system further comprises a chamber defined by chamber walls, wherein the plasma region, the first grid plate, and the second grid plate are housed within the chamber, and wherein the chamber walls are configured to repel ions in the plasma region using a magnetic field. In some embodiments, one or more magnets are coupled to the chamber walls.

In another aspect of the present invention, a method of ion implantation is provided. The method comprises: providing a plasma within a plasma region of a chamber; positively biasing a first grid plate, wherein the first grid plate comprises a plurality of apertures and is disposed in a first position; negatively biasing a second grid plate, wherein the second grid plate comprises a plurality of apertures and is disposed in a first position; flowing ions from the plasma in the plasma region through the apertures in the positively-biased first grid plate; flowing at least a portion of the ions that flowed through the apertures in the positively-biased first grid plate through the apertures in the negatively-biased second grid plate; and implanting a substrate with at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate, wherein the substrate is disposed in a first position.

In some embodiments, a shadow mask comprising a plurality of openings formed therethrough is disposed a predetermined distance away from the substrate, and the method further comprises flowing at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate through the openings in the shadow mask before implanting the substrate.

In some embodiments, a photoresist mask comprising a plurality of openings formed therethrough is placed in contact with the substrate, and the method further comprises

flowing at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate through the openings in the photoresist mask before implanting the substrate.

In some embodiments, the method further comprises: adjusting the position of at least one of the first grid plate, second grid plate, and the substrate holder to a second position; providing a plasma within the plasma region subsequent to the adjustment to the second position; flowing ions from the plasma in the plasma region through the apertures in the positively-biased first grid plate subsequent to adjustment to the second position; flowing at least a portion of the ions that flowed through the apertures in the positively-biased first grid plate through the apertures in the negatively-biased second grid plate subsequent to adjustment to the second position; and implanting a substrate with at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate subsequent to adjustment to the second position, wherein the implantation performed when the at least one of the first grid plate, second grid plate, and the substrate holder was in the first position forms a single laterally-homogeneous ion implantation across the substrate, wherein the single laterally-homogeneous ion implantation is formed from a combination of ions that have passed through different apertures of the second grid plate, and wherein the implantation performed when the at least one of the first grid plate, second grid plate, and the substrate holder was in the second position forms a plurality of laterally spaced-apart ion implantations of the substrate, wherein the plurality of laterally spaced-apart ion implantations is formed from ions that have passed through the different apertures of the second grid plate.

In some embodiments, a third grid plate is disposed between the second grid plate and the substrate, the third grid plate is disposed in a first position and comprises a plurality of apertures configured to allow the ions to pass therethrough subsequent to the ions passing through the second grid plate. In some embodiments, the third grid plate is grounded. In some embodiments, the method further comprises: adjusting the position of at least one of the first grid plate, second grid plate, the third grid plate, and the substrate holder to a second position; providing a plasma within the plasma region subsequent to the adjustment to the second position; flowing ions from the plasma in the plasma region through the apertures in the positively-biased first grid plate subsequent to adjustment to the second position; flowing at least a portion of the ions that flowed through the apertures in the positively-biased first grid plate through the apertures in the negatively-biased second grid plate subsequent to adjustment to the second position; flowing at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate through the apertures in the third grid plate subsequent to adjustment to the second position; and implanting a substrate with at least a portion of the ions that flowed through the apertures in the third grid plate subsequent to adjustment to the second position, wherein the implantation performed when the at least one of the first grid plate, second grid plate, the third grid plate, and the substrate holder was in the first position forms a single laterally-homogeneous ion implantation across the substrate, wherein the single laterally-homogeneous ion implantation is formed from a combination of ions that have passed through different apertures of the third grid plate, and wherein the implantation performed when the at least one of the first grid plate, second grid plate, the third grid plate, and the substrate holder was in the second position forms a plurality of laterally spaced-apart ion implantations of the substrate, wherein the plurality of laterally spaced-apart ion implantations is formed from ions that have passed through the different apertures of the third grid plate.

In some embodiments, the apertures of at least one of the first grid plate and the second grid plate are substantially circular holes. In some embodiments, the apertures of at least one of the first grid plate and the second grid plate are elongated slots. In some embodiments, each one of the apertures of at least one of the first grid plate and the second grid plate comprises a top end and a bottom end, wherein the bottom end is closer to the substrate holder than the top end, and wherein the diameter of each aperture gradually increases from the top end to the bottom end.

In some embodiments, the first grid plate and the second grid plate comprise a material chosen from the group consisting of: silicon, graphite, silicon carbide, and tungsten. In some embodiments, the plasma region, the first grid plate, and the second grid plate are housed within a chamber that is defined by chamber walls, and wherein the chamber walls are configured to repel ions in the plasma region using an electric field.

In some embodiments, the method further comprises the step of applying a pulsed voltage to the plasma. In some embodiments, the method further comprises the step of applying a pulsed voltage to the substrate. In some embodiments, the pulsed voltage is directed towards a plurality of different locations on the substrate.

In some embodiments, the method further comprises: passing the substrate through a first plurality of differentially-pumped stages prior to the substrate being implanted with the ions, wherein each stage in the first plurality of differentially-pumped stages comprises a lower pressure than the previous stage in the first plurality of differentially-pumped stages; passing the substrate from the first plurality of differentially-pumped stages directly to an implantation stage; passing the substrate from the implantation stage directly to a second plurality of differentially-pumped stages subsequent to the substrate being implanted with the ions, and passing the substrate through the second plurality of differentially-pumped stages, wherein each stage in the second plurality of differentially-pumped stages comprises a higher pressure than the previous stage in the second plurality of differentially-pumped stages, wherein the implantation stage comprises a lower pressure than any of the stages in the first plurality and second plurality of differentially-pumped stages.

In yet another aspect of the present invention, a plasma grid implantation system is provided. The system comprises: a plasma source configured to provide plasma; a grid assembly comprising a plurality of grid plates, wherein each grid plate comprises a plurality of apertures configured to allow ions from the plasma to pass therethrough; and a substrate holder configured to support a substrate in a position where the substrate is implanted with the ions subsequent to the ions passing through the plurality of apertures of the grid plates, wherein at least one of the substrate holder and the grid plates is configured to be adjusted between a homogeneous implantation position and a selective implantation position, wherein the homogeneous implantation position is configured to enable a single laterally-homogeneous ion implantation across the substrate on the substrate holder, the single laterally-homogeneous ion implantation being formed from a combination of ions that have passed through different apertures of the second grid plate, and wherein the selective implantation position is configured to enable a plurality of laterally spaced-apart ion implantations of the

substrate on the substrate holder, the plurality of laterally spaced-apart ion implantations is formed from ions that have passed through the different apertures of the second grid plate.

In some embodiments, the plurality of grid plates comprises: a first grid plate comprising a plurality of apertures configured to allow ions from the plasma in a plasma region to pass therethrough; and a second grid plate comprising a plurality of apertures configured to allow the ions to pass therethrough subsequent to the ions passing through the first grid plate. In some embodiments, the first grid plate is configured to be positively-biased by a power supply. In some embodiments, the second grid plate is configured to be negatively-biased by a power supply. In some embodiments, the plurality of grid plates further comprises a third grid plate comprising a plurality of apertures configured to allow the ions to pass therethrough subsequent to the ions passing through the second grid plate. In some embodiments, the third grid plate is configured to be grounded. In some embodiments, the first grid plate, the second grid plate, and the substrate holder are all configured to have their positions adjusted.

In yet another aspect of the present invention, a method of ion implantation is provided. The method comprises: providing a plasma within a plasma region of a chamber; providing a grid assembly comprising a plurality of grid plates, wherein each grid plate comprises a plurality of apertures; flowing a first set of ions from the plasma in the plasma region through the apertures in each of the grid plates in the grid assembly while each of the grid plates is in a first position; homogeneously implanting a substrate with at least a portion of the first set of ions that flowed through the apertures in the grid plates while the substrate is supported in a first position by a substrate holder, thereby forming a single laterally-homogeneous ion implantation across the substrate from a combination of the first set of ions that have passed through different apertures of the same grid plate; adjusting the position of the substrate or at least one of the grid plates to a second position; flowing a second set of ions from the plasma in the plasma region through the apertures in each of the grid plates in the grid assembly subsequent to the adjustment to the second position; selectively implanting the substrate with at least a portion of the second set of ions that flowed through the apertures in the grid plates subsequent to the adjustment to the second position, thereby forming a plurality of laterally spaced-apart ion implantations on the substrate from a portion of the second set of ions that have passed through different apertures of the same grid plate.

In some embodiments, the adjusting step comprises adjusting the position of the substrate. In some embodiments, adjusting the position of the substrate comprises moving the substrate closer to the grid assembly.

In some embodiments, the adjusting step comprises adjusting the position of one of the grid plates. In some embodiments, adjusting the position of one of the grid plates comprises moving one of the grid plates closer to the substrate.

In some embodiments, the plurality of grid plates comprises a first grid plate and a second grid plate, the first grid plate being positively-biased, and the second grid plate being negatively biased. In some embodiments, the plurality of grid plates further comprises a third grid plate that is grounded.

In yet another aspect of the present invention, a method of ion implantation is provided. The method comprises: providing a first single type of dopant material to a plasma generator; the plasma generator breaking up the first single type of dopant material into a first plurality of dopant species; and implanting a substrate with the first plurality of dopant species.

In some embodiments, the substrate is implanted with the first plurality of dopant species in a single implantation step. In some embodiments, each one of the dopant species is implanted into the substrate at a different depth. In some embodiments, the first single type of dopant material is phosphine. In some embodiments, the first plurality of dopant species comprises P^+, P^{++}, P^{+++}, P_2^+, P_3^+, and P_5^+. In some embodiments, the first single type of dopant material is boron or arsenic.

In some embodiments, a combination of different types of dopant material is used to implant different pluralities of dopant species. In some embodiments, the different types of dopant material can be provided in precursor form as gasses, liquids, solids, or any combination thereof.

In some embodiments, a second single type of dopant material is provided to the plasma generator, the plasma generator breaks up the second single type of dopant material into a second plurality of dopant species during the same period that the plasma generator breaks up the first single type of dopant material into the first plurality of dopant species, and the second plurality of dopant species is implanted into the substrate during the same period that the first plurality of dopant species is implanted into the substrate. In some embodiments, the first single type of dopant material and the second single type of dopant material are each a precursor gas. In some embodiments, the first single type of dopant material is arsine and the second single type of dopant material is phosphine.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a cross-sectional side view of one embodiment of a homogeneously doped solar cell in accordance with the principles of the present invention.

FIGS. **2**A-**2**C illustrate cross-sectional side views of different ways of selectively implanting a solar cell in accordance with the principles of the present invention.

FIG. **3** illustrates a cross-sectional side view of one embodiment of a solar cell with contact gridlines in accordance with the principles of the present invention.

FIG. **4** illustrates one embodiment of a plasma immersion implantation system in accordance with the principles of the present invention.

FIG. **5** illustrates a cross-sectional side view of one embodiment of a solar cell with a homogeneous implant in accordance with the principles of the present invention.

FIG. **6** illustrates a cross-sectional side view of another embodiment of a solar cell with homogeneous and selective implants in accordance with the principles of the present invention.

FIG. **7** illustrates a cross-sectional side view of one embodiment of a plasma grid implant system in accordance with the principles of the present invention.

FIG. **8** illustrates a cross-sectional 3-dimensional perspective view of another embodiment of a plasma grid implant system in accordance with the principles of the present invention.

FIGS. **9**A-**9**B illustrate cross-sectional side views of different grid plate apertures in accordance with the principles of the present invention.

FIG. **10** illustrates a cross-sectional side view of one embodiment of plasma ions passing through grid plates in accordance with the principles of the present invention.

FIGS. **11**A-**11**B illustrate plan views of different grid plate apertures in accordance with the principles of the present invention.

FIG. **12** illustrates a plan view of one embodiment of a load-locked implantation system in accordance with the principles of the present invention.

FIG. **13** illustrates a cross-sectional view of one embodiment of a multi-stage differentially pumped implantation system in accordance with the principles of the present invention.

FIG. **14** illustrates a process flow diagram of one embodiment of a method of ion implantation in accordance with the principles of the present invention.

FIG. **15** illustrates a process flow diagram of another embodiment of a method of ion implantation in accordance with the principles of the present invention.

FIG. **16** illustrates a process flow diagram of yet another embodiment of a method of ion implantation in accordance with the principles of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The following description is presented to enable one of ordinary skill in the art to make and use the invention and is provided in the context of a patent application and its requirements. Various modifications to the described embodiments will be readily apparent to those skilled in the art and the generic principles herein may be applied to other embodiments. Thus, the present invention is not intended to be limited to the embodiment shown but is to be accorded the widest scope consistent with the principles and features described herein.

Furthermore, it is contemplated that any features from any embodiment can be combined with any features from any other embodiment. In this fashion, hybrid configurations of the illustrated embodiments are well within the scope of the present invention.

Various aspects of the disclosure may be described through the use of flowcharts. Often, a single instance of an aspect of the present disclosure may be shown. As is appreciated by those of ordinary skill in the art, however, the protocols, processes, and procedures described herein may be repeated continuously or as often as necessary to satisfy the needs described herein. Additionally, it is contemplated that method steps can be performed in a different order than the order illustrated in the figures, unless otherwise disclosed explicitly or implicitly.

The present invention is directed towards an implant system that is not only tailored for the manufacturing of solar cells, but for semiconductor and other surface and near-surface modification applications as well. The development of this system is based on the relaxed specifications that solar cell fabrications require. It can provide accurate doping and unique atomic profile tailoring capability for solar cells (incorporating features from commonly-owned U.S. patent application Ser. No. 12/483,017, entitled "FORMATION OF SOLAR CELL—SELECTIVE EMITTER USING IMPLANT AND ANNEAL METHOD," filed Jun. 11, 2009, and from commonly-owned U.S. Provisional Application No. 61/131,698, entitled "FORMATION OF SOLAR CELL-SELECTIVE EMITTER USING IMPLANT AND ANNEAL METHOD," filed Jun. 11, 2008, which are both hereby incorporated by reference as if set forth herein). These include change in doping levels, resistance of contact, bus bar, fingers, contact resistance of metal-silicon interface, resistance of backside metallization, achieving the desired resistivity under the metal grid contact (preferably 10 to 30 Ohms/Sq.) and in between the fingers (preferably greater than 100 Ohms/Sq.) to meet higher efficiency solar cells (incorporating features from commonly-owned U.S. patent application Ser. No. 12/482,980, entitled "SOLAR CELL FABRICATION USING IMPLANTATION," filed Jun. 11, 2009, commonly-owned U.S. Provisional Application No. 61/131,687, entitled "SOLAR CELL FABRICATION USING IMPLANTATION," filed Jun. 11, 2008, commonly-owned U.S. patent application Ser. No. 12/482,685, entitled "SOLAR CELL FABRICATION WITH FACETING AND ION IMPLANTATION," filed Jun. 11, 2009, and commonly-owned U.S. Provisional Application No. 61/133,028, entitled "SOLAR CELL FABRICATION WITH FACETING AND ION IMPLANTATION," filed Jun. 24, 2008, which are all hereby incorporated by reference as if set forth herein). It also meets the demands of future requirements for solar cell wafer thickness, as well as contact metal width and spacing.

Moreover, the advantageous formation of selective emitter and Back Surface Field (BSF) and its ability to improve performance will be possible (incorporating features from commonly-owned U.S. patent application Ser. No. 12/482,947, entitled "APPLICATION SPECIFIC IMPLANT SYSTEM AND METHOD FOR USE IN SOLAR CELL FABRICATIONS," filed Jun. 11, 2009, commonly-owned U.S. Provisional Application No. 61/131,688, entitled "APPLICATIONS SPECIFIC IMPLANT SYSTEM AND METHOD FOR USE IN SOLAR CELL FABRICATIONS," filed Jun. 11, 2008, commonly-owned U.S. Provisional Application Ser. No. 61/210,545, entitled "ADVANCED HIGH EFFICIENCY CRYSTALLINE SOLAR CELL FABRICATION METHOD," filed Mar. 20, 2009, and commonly-owned U.S. patent application Ser. No. 12/728,105, entitled "ADVANCED HIGH EFFICIENCY CRYSTALLINE SOLAR CELL FABRICATION METHOD," filed Mar. 19, 2010). The present invention can be applied to as-grown single or mono-crystalline, poly or multi-crystalline or electrical-grade or metallurgical-grade silicon, as well as very thin silicon wafers and very thin film deposited silicon, or other materials used for solar cell formation and other applications. The present invention can also be applied to multi junction devices, and can be extended to atomic species placement for any other material used in fabrication of junctions and metal semiconductor interface enhancements.

FIG. **5** illustrates a cross-sectional side view of one embodiment of a solar cell **500** with a homogeneous implant in accordance with the principles of the present invention. Solar cell **500** comprises a semiconducting wafer with a p-doped region **510** and an n-doped region **520**. Then—doped region **520** is homogeneously doped to form a homogeneous emitter. An anti-reflective coating **560** is disposed over then-doped region **520**. The anti-reflective coating **560** preferably has a thickness of between 70-80 nm. Metal contacts **550** are deposited onto the wafer, preferably having a width **554** of between 3-200 microns and being spaced apart by a width **552** of between 1-3 mm. A p-doped region **570** is formed in the wafer on the opposite side from the n-doped region **520**, forming a homogeneous BSF. A passivation layer **580** (e.g., Si_3N_4 or Al_2O_3) is disposed over the bottom surface of the p-doped region **570**, and a rear metal contact layer **590** (e.g., Ag) is disposed over the bottom surface of the passivation layer **580**.

FIG. **6** illustrates a cross-sectional side view solar cell **600**, which is solar cell **500** with the addition of certain selective implants. These selective implants include n-doped

selective emitter regions **630**, selective metallic seed implants **655**, and selective BSF regions **675**.

In some embodiments, the present invention includes the use of ions in gas plasma that are accelerated to the substrate by the application of pulses of negative potential to the substrate. The plasma is transitioned into a sheath at the proximity of the substrate, and applications of a potential cause acceleration of ions resident in the plasma to be implanted. Such conformal doping of the substrate can be utilized to form homogenous doped regions, as well as selectively doped regions through the use of a mask or other selective implantation techniques. At the same time, the dopant profile can be tailored to provide independent surface concentrations, shape of the profile, and the junction depth, through pulse shape and plasma component adjustments. Furthermore, through the use of the dopant stoichiometric ratio and ratio of molecular radicals, the dopant profile can be further enhanced. Utilization of the pulse biasing of the substrate and possible substrate back surface antenna or substrate movement can also provide the lateral positioning advantages required for selective implantations.

The present invention provides a system that can be independent of the substrate size, and as long as uniformity of plasma is conserved, then multiple pieces of substrate can be implanted simultaneously. This feature allows productivities well in excess of 1000+ wph. Additionally, the present invention provides a non-line-of-sight implantation method, and thus, is able to dope areas that are constricted, such as the textured surfaces of multi-grade silicon that may have hillocks and re-entrant features on the surface. Doping such surfaces is critical as absence of doping may cause metal shunting.

One application of the present invention is to generate a homogeneous implantation for emitter and Back Surface Field (BSF) doping. At this stage, independent control of surface concentration, profile shape and junction depth can play a significant role in meeting the light conversion properties of a solar cell. Such implant capabilities will avoid the formation of a "dead layer" that is prevalent with incumbent diffusion methods. These layers are formed as a result of un-activated excess near-surface dopants that are accumulated as diffusion is used to form the electrical junctions. Profile management achieved with the present invention's ion implantations can avoid such drawbacks.

FIG. **1** illustrates a cross-sectional side view of one embodiment of a homogeneously doped solar cell **100** in accordance with the principles of the present invention. Solar cell **100** comprises a semi-conducting substrate **110**, such as a silicon wafer. For the formation of the region **120** where the cell **100** generates the electron-hole pairs, doping levels of at least 100 Ohms/Sq. is preferred. In general, the excess of dopants in this region **102** impede the generation and transport of such charge carriers. This doping is typically a lower energy implant, such as less than 150 keV for boron, BF_2, phosphorous, arsenic, antimony, and other similar dopants. Such implants are carried out at a light concentration. In a preferred embodiment, the concentration of these implants is less than 1E15 cm^{-2}. The requirements for the uniformity of coverage for solar cell applications are estimated to be between 5 to 10%. Similar homogeneity is required in the plasma uniformity. It is envisaged that each solar cell will be independently implanted, so as to attain the benefits of the single wafer system. This feature provides significant capability for implant, whereby tailoring the placement and activation of the dopant for selective emitter can prevent the formation of the traditional dead layer issues.

FIGS. **2**A-**2**C illustrate cross-sectional side views of different ways of selectively implanting a solar cell **200** to form selective emitter regions **230** in accordance with the principles of the present invention. The solar cell **200** comprises a semi-conducting substrate **210**, which has been homogeneously doped to form a homogeneous emitter region **220**, similar to homogeneous emitter region **120** in FIG. **1**.

FIG. **2**A illustrates a shadow mask method used to form selective emitter regions **230** in the semi-conducting substrate **210**. In the shadow mask method, a physical mask **242** is used within the plasma implanter technologies system to define the beam **240** to the exact dimension required. The aspect ratio of the mask **242** is critical here, as it is estimated that typical energetic plasma ions can easily penetrate a 1:10 aspect ratio, as has been demonstrated by lower energy plasma deposition methods. The proximity of the mask **242** to the substrate **210** can be adjusted to use potential beam flare-out to the advantage of construction of doped regions under the gridlines that are larger by approximately +/−10 to 30 microns for a 100 micron wide gridline. This adjustment will allow for ease of subsequent gridline printing and alignment, and will provide an overlapping region for minimization of any potential electrical leakage. In a preferred embodiment, the material used for the shadow mask **242** is innocuous to the processing, and is preferably conductive in order to not affect the implantation method. Sputtering of such material will determine the lifetime and usage of this mask **242**, thus rendering it a consumable component with a regular replacement provision. The shape of the cutouts through which the ion beams **240** pass and surface conditions are also of critical considerations to minimize contamination and sputtering rates. Typical shaping that is already prevalent in the industry can be used for the fabrication of the shadow mask **242**.

FIG. **2**B illustrates a wafer mask method used to form selective emitter regions **230** in the semi-conducting substrate **210**. Here, a mask **244** is placed in contact with the semiconducting wafer **210**. Such mask **244** can be a hard or soft masking of the wafer prior to the implant step. The wafer mask method can be achieved through the use of lithography, contact printing, or more prevalent screen printing steps. It can also utilize the already masked and opened processing steps used for formation of contact deposition. The distributed power density of this implantation method can lead to utilization of masking materials that were not used in the past implantation methods. An example of such materials is the use of resist that is used, traditionally, in circuit board fabrications and other low temperature masking materials.

FIG. **2**C illustrates a localized plasma beam shaping method to form selective emitter regions **230** in the semi-conducting substrate **210**. Here, the required pulsing of the beam and an envisaged back surface antenna can be made into a closed loop control so that plasma is directed selectively into certain regions of the substrate. In some embodiments, additional grid structures, such as those discussed in further detail below, could be used to further optimize the shape of the plasma beam, whereby a voltage can be applied, both negative and/or positive, to achieve such shaping. As seen in FIG. **2**C, the selected regions **230** are in alignment with the locations where a voltage **246** is directly applied to the back surface of the semiconducting wafer **210**. This method may be more applicable for thinner wafers. Alternatively, a combination of the pulsing of the plasma and possible positioning of the substrate can be used to generate areas of high and low doping. Overlapping of these regions can provide an optimized controlled flow of electron holes

from the low-doped regions, suited for light conversion, to the highly-doped selectively implanted regions, suited for electrical contact gridlines. One could envisage regions of high and low doping overlaps as the substrate, under precise controlled motions, moves beneath the ion beams. The different regions will not have distinctive boundaries, and a gradual change of doping levels can provide an advantage in flow of charges within the substrate. Such variability in the lateral doping can enhance the operation of the cells.

FIG. **3** illustrates a cross-sectional side view of one embodiment of a solar cell **300** with contact gridlines **350** in accordance with the principles of the present invention. The solar cell **300** comprises a wafer. In some embodiments, the wafer **110** is a 156×156 mm wafer. Preferably, the wafer is formed of a semiconductor material, such as silicon (single or multi-crystalline), and comprises a p-njunction. The p-njunction is formed from a p-type doped region **310** and an n-type doped region **320** being disposed next to one another. Metal contact lines **350** are printed, or otherwise formed, on the surface of the wafer. It is contemplated that the contact lines **350** can also be formed from conductive material other than metal. In some embodiments, conductive fingers (not shown) are also disposed on the surface of the wafer to collect the electrical charge from the contact lines and carry it out to an external load.

In operation, as light comes into the semiconductor material of the wafer through the exposed surface between the contact lines **350**, it is converted into electron-hole pairs, typically within then-type doped region **320**. The electrons go one way, getting attracted into the contacts **350**, while the holes go the other way, towards the p-type doped region **310**. The more dopant there is within a particular region, the more the electron-hole pairs are recaptured within that region, resulting in more lost electricity. Therefore, it is beneficial to control the level of doping for different regions. In regions where the light is to be converted into electron-hole pairs, the level of doping should be relatively low. In regions where the charge is to go through the contact lines **350**, the level of doping should be high. Regions **320** represent a homogeneous emitter region that has been homogeneously doped with a low level of n-type dopant. Regions **330** disposed beneath the contact lines **350** near the surface of the wafer represent selective emitter regions that have been selectively doped with a relatively high level of n-type dopant.

As a result of minimizing the dopant concentration (thereby, maximizing the resistivity) of the homogeneous emitter region and maximizing the dopant concentration (thereby, minimizing the resistivity) of the selective emitter regions, the ability of the solar cell to transfer the generated electrons from the homogeneous emitter region through the selective emitter regions to the contact lines is increased, while the risk of losing electricity to electron-hole pair recombination is reduced. Additionally, although bigger contact lines can conduct more electricity, they also block more light from entering the solar cell and being converted into electrons. By maximizing the dopant concentration of the selective emitter regions near the contact lines, the contact lines can actually be made thinner, thereby allowing more light to enter the solar cell, while improving the solar cells ability to transfer the electrons from the electron-hole pair generating region to the contact lines.

In some embodiments, the homogeneously doped region is doped to have a sheet resistance in a range of approximately 80 Ohms/square to approximately 160 Ohms/square, while the selectively doped regions are doped to have a sheet resistance in a range of approximately 10 Ohms/square to approximately 40 Ohms/square. In some embodiments, the homogeneously doped region is doped to have a sheet resistance of approximately 100 Ohms/square or greater, while the selectively doped regions are doped to have a sheet resistance of approximately 25 Ohms/square or less.

In some embodiments, the selectively doped regions **330** are laterally spaced apart from one another a distance in the range of approximately 1 mm to approximately 3 mm. However, it is contemplated that other spacing dimensions are within the scope of the present invention. Additionally, for selective emitter applications, the solar cell industry is expected to require the implanted contact gridlines **350** to have a width from 200 microns down to less than 50 microns.

Plasma implantation systems can be used for the formation and adjustment of the work function and the band gap engineering for the contact deposition, through the formation of near-surface metal-silicide. Through a very light dose implantation of a metallic species (such as Ta, Ti, etc.) at locations near the surface of the wafer, a metal/silicon contact is improved markedly. Such seed implants or work function adjustment implants can improve contact performance.

FIG. **4** illustrates one embodiment of a plasma immersion implantation system **400** in accordance with the principles of the present invention. This system is disclosed in U.S. Provisional Application Ser. No. 61/185,596, filed Jun. 10, 2009, entitled "APPLICATION SPECIFIC PLASMA IMPLANT SYSTEM FOR USE IN SOLAR CELL FABRICATIONS," which is hereby incorporated by reference in its entirety as if set forth herein. The system **400** comprises a vacuum chamber **410**, a gas input system **420**, a plasma generator **430**, one or more vacuum pumps **450**, and a high-voltage pulser **480**. The gas input system **420**, the plasma generator **430**, and the vacuum pumps **450** work together to provide plasma **460** within the vacuum chamber **460** at a location near a target substrate **440**. The high-voltage pulser **480** is used to negatively bias the target substrate **440**. Examples of pulsers that can be used include hard-tubed pulsers, such as planar triode, power tetrode, and hobertron. It is contemplated that other pulsers can be used as well. As a result of the high negative voltage pulse being applied to the target substrate **440**, a sheath between the plasma **460** and the target substrate **440** forms, and ions **470** from the plasma **460** are accelerated into the target substrate **440**. This plasma immersion implantation technique removes the need for any mass analysis. It provides acceptable power density and excellent productivity.

This implantation system has unique capabilities for solar cell applications. In order to meet the productivity demand of the solar cell industry, multiple-piece simultaneous implantation is envisaged. For a typical four-piece substrate of 156×156 mm pseudo-square, with a total area of 0.25 m^2, such a system will preferably comprises a large plasma, with a height of 0.3 m and a sheath of 0.5 cm, and a total chamber height of 1 m, with generation of plasma peak currents up to 15 A. The system is useful in meeting the pulse energy demands of the solar field, which are variable and preferably less than 150 kV. These supplies will be plug compatible and, depending on the species and mass used, will provide the required depth of penetration.

In some embodiments, the system is used for single species implantation, so as to avoid any cross contamination of dopants. Additionally, in some embodiments, the internal portion of the chamber **410** is clad with appropriate material so as to minimize the potential of metallic and other unwanted contamination.

Preferably, components such as the vacuum chamber, multiple-pass load lock, gas delivery system, and automation and factory interfaces are configured in-line with such an application specific system or in-line with a typical high volume solar cell manufacturing system. In preferred embodiments, the system operates with a productivity of 1000+ wafers per hour to match the automation of the solar cell fabrication lines.

The dopant profile can be modified through the pulse shape adjustment to meet the tailoring required by solar cell PV fabrications. One method is to use a passivation pulse-forming network mechanism. The profile can further be tailored by the use of plasma content adjustment, which can be achieved through the special use of micro-wave or RF coupling, or any multiple of prevalent plasma formation technology, with plasma so as to modify the plasma conditions and thus control the break up of the constituents, which can affect the stoichiometric ratio of the dopant and the molecular ratio of radicals present in the plasma. For example, for the use of solid phosphorous, its various components (such as P^+, P^{++}, P^{+++}, P_2^+, P_3^+, P_5^+, etc.) can be used to ensure that near surface tailoring is achieved. Such tailoring can also be used for other dopants, such as p-type Boron.

A direct side benefit of plasma implant technology is the prevalence of hydrogen (e.g., if the source of the dopant is PH_3 or B_2H_6). The hydrogen will be implanted simultaneously and at higher energies, helping to provide an auto-gettering effect that is unique and demanded for poorer quality solar cell materials.

Variability of the energy during the pulsing of the plasma, where it can be distinct or as a continuum, can also be employed to form the required profile and manage independent surface concentration, atomic profile shaping and junction depths. This could be distinct and in known steps or can be as continuum to appropriate pauses at required energy to contrast the desired profiles.

The average distributed power density of this system lends itself to implantation of very thin wafers (i.e., less than 20 microns) and ensures that thicker wafers remain at a temperature of less than 100° C. throughout the process. Such distributed power density allows utilization of various hard masking (e.g., resist) materials that may not have been considered before with diffusion, which employs high temperature, and directed implant, which employs high average power density. Depending on the desired PV applications, the average distributed power density of the present invention can be modulated by adjusting the frequency and duration of pulses for high (greater than 300° C.) and low (less than 100° C.) substrate temperature.

No subsequent diffusion is required. Lower temperature anneal as low as 500° C. can provide enough activation and damage anneal for fabrication of a PV cell. Plasma implantation, due to its high productivity, can provide higher doses, and thus, if only a portion of the dopant is activated, then the desired resistivity and performance can be achieved.

In some embodiments, various materials or compounds are used to provide surface passivation in solar cell fabrication. For example, in some embodiments, Si_3N_4 or SiO_2 is deposited and/or grown at elevated temperatures or using pyrogenic growth methods. Such methods are limited to prevalent chemistry and molecular make up cannot be changed. However, through the use of the plasma implant technology of the present invention, the molecular make-up can be adjusted for improvements of passivation properties. Formation of SiNx or introduction of excess nitrogen can provide improvement of passivation properties of this film.

Despite the advantages of the plasma immersion implantation system discussed above, the present invention provides an even more beneficial implantation system in the form of a plasma grid implantation system. The plasma grid implantation system provides the beneficial power density of beamline implantation, while also providing the productivity of plasma immersion technology.

FIG. **7** illustrates a cross-sectional side view of one embodiment of a plasma grid implant system **700** in accordance with the principles of the present invention. System **700** comprises a chamber **710** that houses a first grid plate **750**, a second grid plate **755**, and a third grid plate **757**. The grid plates can be formed from a variety of different materials, including, but not limited to, graphite, silicon carbide, and tungsten. Each grid plate comprises a plurality of apertures configured to allow ions to pass therethrough. A plasma source provides a plasma to a plasma region of the chamber **710**. In FIG. **7**, this plasma region is located above the first grid plate **750**. In some embodiments, the chamber walls are configured to repel ions in the plasma region using an electric field. For example, in some embodiments, one or more magnets **790** are coupled to the wall of the chamber **710**. The electric field is used to push the plasma off the walls, thereby maintaining a gap between the plasma and the chamber walls, and avoiding any sputtering off of the wall material into the plasma. A target substrate is positioned on the opposite side of the grid plates. In FIG. **7**, the target substrate is located below the third grid plate **757**. As will be discussed in further detail below, the target substrate is preferably supported by an adjustable substrate holder, thereby allowing the target substrate to be adjusted between a homogeneous implant position **740***a* and a selective implant position **740***b*.

The main feature of this system **700** is the use of plasma ions that are accelerated towards the target substrate by application of a DC or pulsed potential to the first grid plate **750**. These ions are implanted into the substrate. The deleterious effect of secondary electrons resulting from the impingement of ions on the substrate and other materials is avoided through the use of the second grid plate **755**, which is negatively-biased with respect to the first grid plate **750**. This negatively-biased second grid plate **755** suppresses the electrons that come off of the substrate. In some embodiments, the first grid plate **750** is biased to 80 kV and the second grid plate **755** is biased to −2 kV. However, it is contemplated that other biasing voltages can be employed. The third grid plate **757** acts as a beam defining grid and is preferably grounded. It is positioned in contact with or very close to the surface of the substrate in order to provide a final definition of the implant. This grid plate **757** can act as a beam defining mask and provide the critical alignment required, if a selective implant is required. The third grid plate **757** can be configured in accordance with the shadow mask embodiment of FIG. **2**A or the wafer mask embodiment of FIG. **2**B in order to achieve beam-defining selective implantation. Additionally, the third grid plate **757** can be replaced or supplemented with any form of beam shaping that does not require a mask, such as the pulsed beam shaping embodiment of FIG. **2**C.

It is contemplated that the grid plates can be spaced apart in a variety of ways. In one embodiment, the first grid plate **750** is separated from the second grid plate **755** by a distance of approximately 12 mm, and the second grid plate **755** is separated from the third grid plate by a distance of approximately 3 mm. However, other measurements can be employed.

In general, several grid arrangements, such as triode, tetrode and others, can be envisaged, where the grid arrangements are used to optically control the ion beam-lets. For the case of homogenous implantation, the defining mask can be removed to provide homogenous coverage of the wafer. The position of the wafer for selective implantation, with shadow mask, and for homogenous implantation can be altered to benefit from the multiple grids beam definition. For example, for the selective implantation, the wafer **740***b* is moved close to the multiple grid plate assembly (**750**, **755**, **757**), whereas, for the homogenous implantation, the wafer **740***a* is moved far enough from the grid plate assembly (**750**, **755**, **757**) to provide a uniform beam, which is formed as a result of space charge expansion of the beam-lets **776**. This grid plate assembly can be used to further focus the beam-lets **776** into known shapes onto the substrate, such as by adjusting the position of the plates with respect to one another, thereby eliminating the need for any shadow masking or any other substrate masks. This grid plate assembly arrangement enables the use of DC or pulsed bias for the acceleration of ions and minimizes the back streaming electrons that has hampered plasma immersion technology by limiting the energy range and making the pulser/PSU cost prohibitive. This dramatically simplifies the power supply needed.

Additionally, by decoupling the plasma formation from the ion acceleration, the present invention allows for independent methods to be used for the formation of the plasma above the grid plates. The grid plates can provide some degree of beam definition. For example, the extracted ion beam can be focused to a particular dimension of selective emitter applications.

In plasma grid implant system **700**, the chamber **710** is configured to allow the plasma to form and expand. As previously discussed, the first grid plate **750** is at a positive potential with respect to ground. By shaping this biased grid plate (electrode) and managing the shape of the meniscus **780** formed above each of its openings, ions are extracted and optically shaped.

As previously discussed, the second grid plate **755**, which is negatively biased, suppresses the back streaming electrons. The substrate and the third grid plate **757** (whether it is configured as a shadow mask or a wafer mask) can be placed at a very close proximity to the second grid plate **755** to utilize the pattern definition by the grid assembly, as shown with the position of substrate **740***b*. At this position, the ions extracted are in the shape of beam-lets that are well defined and implanted in selective regions in the substrate **740***b*. The substrate can also be positioned further away from the first and second grid plates **750** and **755** to achieve a homogenous and uniform implant either with or without the use of a shadow mask, such as with substrate **740***a*. As seen with the positioning of substrate **740***a*, the beam-lets **776** have merged due to space charge expansion. Alternatively, one position could be used for both homogeneous and selective implantation, where the selective implant is performed in the presence of a shadow mask or a wafer mask in order to provide the selectivity required.

A beam of ions exiting past an aperture is divergent by its nature, which is because the typical equilibrium of plasma is convex. The ions repel each other because of their like electric charge and they have randomly orientated velocities due to thermal motion within the plasma. Therefore, careful design of the grid plate apertures and the plasma condition is necessary to control both the emittance of ions and system acceptance to the ion beam. The emittance is a measure of the beam quality. Typically, high quality beams have low emittance, which means minimal loss of ions during transmission. This has to be balanced against the system specific phase-space boundary such that the beam fits within this boundary or has good acceptance.

The control of ion divergence in the system of the present invention is achieved primarily through adjusting the shape of the ensuing meniscus **780** at the plasma boundary as it enters the first grid plate electrode **750**. Such shaping can be controlled by adjusting the voltage difference between various electrodes, the shapes of the opening and spacing between various electrodes, the temperature of the plasma, how much plasma gas is used, the density of the plasma and the ion species and current being extracted. For the concave dome shape of meniscus **780** in FIG. **7**, the second grid plate **755** has to have a negative potential with respect to the first grid plate **750**, and the plasma ion density has to be less than the plasma boundary. Although FIG. **7** shows meniscus **780** having the shape of a dome, it is contemplated that the meniscus **780** can be managed in the form of other shapes as well, including, but not limited to, a complete inversion of the dome shape. The shape of the meniscus **780** can be used to shape the resulting ion implantation beam. Whereas a dome-shaped meniscus, such as meniscus **780** shown in FIG. **7**, will typically result in a narrowed beam, an inverted dome-shaped meniscus will typically result in an expanding beam.

FIG. **8** illustrates a cross-sectional 3-dimensional perspective view of another embodiment of a plasma grid implant system **800**, similar to system **700**, in accordance with the principles of the present invention. System **800** comprises a chamber **810** that houses a first grid plate **850**, a second grid plate **855**, and a third grid plate **857**. The grid plates can be formed from a variety of different materials, including, but not limited to, silicon, graphite, silicon carbide, and tungsten. Each grid plate comprises a plurality of apertures configured to allow ions to pass therethrough. A plasma source provides a plasma to a plasma region of the chamber **810**. In FIG. **8**, this plasma region is located above the first grid plate **850**. In some embodiments, a plasma gas is fed into the plasma region through a gas inlet **820**. In some embodiments, a vacuum is applied to the interior of the chamber **810** through a vacuum port **830**. In some embodiments, an insulator **895** is disposed around the exterior wall of the chamber **810**. In some embodiments, the chamber walls are configured to repel ions in the plasma region using an electric field, as discussed above.

A target wafer **840** is positioned on the opposite side of the grid plates from the plasma region. In FIG. **8**, the target wafer **840** is located below the third grid plate **857**. As previously discussed, in some embodiments, the target wafer **840** is supported by an adjustable substrate holder, thereby allowing the target wafer **840** to be adjusted between a homogeneous implant position (closer to the grid plates) and a selective implant position (farther away from the grid plates). Plasma ions are accelerated towards the target wafer **840** by application of a DC or pulsed potential to the first grid plate **850** in the form of ion beams **870**. These ions are implanted into the wafer **840**. The deleterious effect of secondary electrons resulting from the impingement of ions on the wafer **840** and other materials is avoided through the use of the second grid plate **855**, which is negatively-biased with respect to the initial grid. This negatively-biased second grid plate **855** suppresses the electrons that come off of the wafer **840**. In some embodiments, the first grid plate **850** is biased to 80 kV and the second grid plate **855** is biased to −2 kV. However, it is contemplated that other biasing voltages can be employed. The third grid plate **857** acts as

a beam defining grid and is preferably grounded. It is positioned in contact with or very close to the surface of the substrate in order to provide a final definition of the implant.

This grid plate **857** can act as a beam defining mask and provide the critical alignment required, if a selective implant is required. The third grid plate **857** can be configured in accordance with the shadow mask embodiment of FIG. **2**A or the wafer mask embodiment of FIG. **2**B in order to achieve beam-defining selective implantation. Additionally, the third grid plate **857** can be replaced or supplemented with any form of beam shaping that does not require a mask, such as the pulsed beam shaping embodiment of FIG. **2**C.

It is contemplated that the apertures in the grid plates can be configured in a variety of different ways. FIGS. **9**A-**9**B illustrate cross-sectional side views of different grid plate apertures through which the ion beams pass. In FIG. **9**A, grid plate **950***a* comprises an aperture **965***a* that has a uniform width. When the grid plate **950***a* is positively-biased, an electric field is formed around it. This electric field is illustrated by electric field lines **951***a* and **953***a*, which follow the contour of the grid plate **950***a*. As an ion beam passes through the aperture **965***a*, field lines **951***a* and **953***a* define the path along which the ions travel. As a result, the electric field chokes the ions as they pass through the aperture **965***a*, thereby narrowing the width of the resulting ion beam. In FIG. **9**B, grid plate **950***b* comprises an aperture **965***b* that has a width that expands from top to bottom. Similar to grid plate **950***a* in FIG. **9**A, when the grid plate **950***b* is positively-biased, an electric field is formed around it. This electric field is illustrated by electric field lines **951***b* and **953***b*, which follow the contour of the grid plate **950***b*. As an ion beam passes through the aperture **965***b*, field lines **951***b* and **953***b* define the path along which the ions travel. Since the width of the opening **965***b* expands as from the point where the ions enter the aperture **965***b* to the point where the ions exit the aperture **965***b*, this aperture configuration provides a resulting ion beam that can cover a larger surface area than the uniform configuration.

FIG. **10** illustrates a cross-sectional side view of one embodiment of plasma ions passing through grid plates in accordance with the principles of the present invention. Similar to FIGS. **7**-**8**, a plasma **1060** is provided above first and second grid plates **1050** and 155, which are positively and negatively biased, respectively, as previously discussed. A meniscus **1080** is formed at the plasma boundary as the plasma ions enter aperture of the first grid plate electrode **1050**. The ion beam **1070** passes through the first grid plate electrode **1050** and then through the second grid plate electrode **1055** before implanting a target substrate disposed below the grid plate assembly. The top and bottom surfaces of the grid plates can be configured to manage the ion beam **1070** in a variety of ways. For example, in some embodiments, the bottom surface **1052** of the first grid plate 105 can be angled inward in a female configuration and the top surface **1054** of the second grid plate **1055** can be angled outward in a male configuration so that the entrance to the aperture in the second grid plate **1055** can be brought closer to the exit of the aperture in the first grid plate **1050**.

FIGS. **11**A-**11**B illustrate plan views of different grid plate apertures in accordance with the principles of the present invention. FIG. **11**A shows grid plate **1050***a* having a plurality of apertures **1165***a* formed therethrough. These apertures **1165***a* are substantially circular. FIG. **11**B shows grid plate **1050***b* having a plurality of apertures **1165***b* formed therethrough. These apertures **1165***b* are substantially elongated and rectangular slots. In some embodiments, the elongated slots **1165***b* have dimensions of a few 100's of microns wide by 10's of centimeters long at a spacing of 1-2 mm in order to maximize the utilization of the plasma beam-lets and create the image of the final beam-defining grid. However, larger spacing could be envisaged, whereby the space charge beam expansion is employed to get a uniform beam to provide the coverage needed. It is contemplated that the apertures can be formed in other shapes besides circular and rectangular. The shape and the dimensions of the openings in the grid plates depend on the shape and dimension of the series of beam-lets required for the particular implantation. Beam optics calculations and considerations, such as emittance and space charge effects, define the shape of such openings and the materials utilized for the fabrication. The opening in the first grid plate is particularly critical in order to maintain the shape of the resulting meniscus of plasma at the grid plate openings. The shape of this meniscus is critical for the subsequent optical properties of the ion beam. The position, shape, and applied negative potential field at the second grid plate and its possibility of interference in the shape of the meniscus is critical to ensure passage of the ion beam with minimum ion optical effect, while still being sufficient to inhibit flow of electrons in the reverse direction.

The combination of the two, three or more grid plates simplifies the DC or pulsed power supply units for energizing the grid plates. For these applications, an accelerating potential of less than 150 kV is envisaged, with a negatively biased grid plate of approximately −5 kV. The grid plate spacing between the first grid plate and the second grid plate in a reasonable vacuum is preferably in the order of a few centimeters, while the spacing between the second grid plate and the third grid plate is preferably in the order of a few millimeters. Certain calculations and distances in vacuum can be used for the applied voltage.

The second grid plate electrode can also be connected to a pulse forming network to optimize the extracted ion qualities, such as increased density of desired ion species and ion energy, in order to optimize the implanted junction profile. The plasma source in the chamber can also be pulsed-biased using the similar pulse-forming network in modulation with that of the second grid plate electrode in order to optimize the extracted ion qualities as mentioned in above.

The system of the present invention provides a simplified arrangement that lends itself well into formation of implant chambers, as opposed to single beam (including widened beams) and scanning mechanisms that have made ion implantation systems into complex multi-module systems. Such simple ion beam generation (via plasma) and ion acceleration (via grid plate assembly) can be constructed into a single chamber assembly that can be combined with a general wafer handling platform. Such a platform can support other processes in the fabrication lines, such as vacuum deposition, etching and metallization. FIG. **12** illustrates a plan view of one embodiment of a load-locked implantation system **1200** in accordance with the principles of the present invention. The target wafer can be loaded into a vacuum chamber **1210**, where a robot can then transfer the wafer to one of several load-locked chambers under vacuum. For example, the wafer can be moved into one of several implantation systems **1220**, such as system **700**. The wafer can also be moved into a nitridization chamber **1230** or an oxidation and anneal chamber **1240**, such as an RTP anneal chamber.

Furthermore, such a platform can support a multi-stage vacuum pumping scheme that denies the need for specific load-locking mechanisms. FIG. **13** illustrates a cross-sec-

tional view of one embodiment of a multi-stage differentially pumped implantation system **1300** in accordance with the principles of the present invention. In the system, the target wafer **1380** is moved through multiple stages before and after reaching the implantation stage. In some embodiments, the wafer **1380** is moved via a conveyor belt **1390**. However, it is contemplated that other transfer means can be employed. In FIG. **13**, the wafer **1380** moves from right to left, going through stage **1310**, then stage **1320**, and then stage **1330**, before reaching stage **1340**, with each stage applying a stronger vacuum. Stage **1310** applies a small vacuum VI (e.g., resulting in a pressure of 0.1 millibars). Stage **1320** applies a larger vacuum V**2** than stage **1310** (e.g., resulting in a pressure of 0.01 millibars). Stage **1330** applies an even larger vacuum V**3** than stage **1320** (e.g., resulting in a pressure of 10^{-4} millibars). Finally, Stage **1340** applies the largest vacuum V**4**. At stage **1340**, the plasma grid implantation system discussed above is used, employing the multiple grid plate assembly (e.g., grid plates **1342** and **1344**). Once the implantation stage is completed, the wafer **1380** moves through stage **1350**, then stage **1360**, and finally stage **1370**, each stage applying a smaller vacuum than the last stage.

The vacuum chamber, multiple pass load lock or multi-staged differentially-pumped pass-through, gas delivery system and automation and factory interfaces can also be configured in-line with an application specific implantation system or configure in-line with a typical high volume solar cell manufacturing system. Preferably, the productivity of the system is 1000+ wafers per hour to match the automation of the solar cell fabrication lines.

For homogenous implantation for emitter and back surface field (BSF) doping, independent control of surface concentration, profile shape and junction depth can play a significant role in meeting the light conversion properties of a solar cell. Such implant capabilities will avoid the formation of "dead layer" for emitter, which is prevalent with incumbent diffusion methods. These layers are formed as a result of un-activated excess near surface dopants accumulated as diffusion is used to form the electrical junctions. Profile management achieved with ion implantation can avoid such drawbacks. The BSF implant can be used to displace the present method of aluminum metallization that is encumbered with a series of mismatch issues. The control for such BSF implantation will also provide key advantages in the formation of back contact.

For the formation of the regions where cells generate the electron hole pairs, doping levels of at least 100 Ohms/Sq. is preferably used. In general, the excess of dopants in this region impedes the generation and transport of such charge carriers. This region is typically a lower energy implant, such as less than 150 keV for boron, BF2, phosphorous, arsenic, antimony, and other similar n or p-type dopants. Such implants are carried out at a dose of less than 1E16 cm^{-2}. The requirements for the uniformity of coverage for solar cell applications are estimated to be between 5 to 10%. This requires similar homogeneity in the plasma uniformity. It is envisaged that each solar cell will be independently implanted, so as to attain the benefits of the single wafer system, which is a significant capability for implantation, whereby tailoring the placement and activation of the dopant for the selective emitter regions can avoid the formation of the traditional dead layer issues. As implantation is a single sided process, there will be no necessity for the edge etch or cutting of the solar cells.

This capability is achieved by positioning the target substrate underneath the grid assembly electrodes only at a distance far enough where the beam-lets have converged due to space charge expansion to a uniform beam. This positioning can be achieved through the use of an elevator that moves the target substrate to and away from the grid assembly. The plasma intensity variation and variation of the potential on the second grid plate and, at times, on the first grid plate also provide the uniformity of less than 5% (one sigma) in the beam.

As mentioned above, another application of the present invention is to use some form of masking to generate selectively implanted regions. Such regions can be n or p-type depending on whether it is for a selective emitter or a selective BSF. It can also be a series of interdigitated alternate doping (n/p/n/p . . . etc.) regions for all back contact solar cells. For this application, the target substrate plus the mask could be held very close to the grid assembly, where the beam-lets are much more distinct and spaced apart. Alternatively, one could rely on the shadow mask at the wafer to provide the implant selectivity required. The dimensions of the grid plate openings can match the substrate mask for best utilization of the ion beam. Although, this is not critical as presence of the mask on the wafer will ensure selectivity.

In another embodiment, the plasma grid implant system of the present invention is used for the formation and adjustment of the work function and the band gap engineering for the metal/semiconductor contact regions. In this step, through metallic species implantation at locations very near the surface, metal/silicon contact is improved markedly. A similar system, as discussed above, can be used to do the grid line implants after the selective doping implants. Such seed implants or work-function-adjust implants can improve contact performance.

The control of the dopant atomic profile can also be made through the prevalence of multiple species available in a plasma. Each plasma condition will have a mix of charged species at varying fractions. Such fractions can be controlled and are repeatable. Such mixed species is of the desired atoms at molecular and multiple charge state and, for the same applied voltage bias, will have varying energies. For example, a single type of dopant material can be provided to a plasma generator, where it is broken up into a plurality of dopant species. The target substrate is then implanted with the plurality of dopant species. For example, using a plasma gas such as phosphine, can provide different types of implants with only one implantation step because of the different charges and different masses of the resulting dopant species (P^+, P^{++}, P^{+++}, P_2^+, P_3^+, P_5^+, etc.) that are formed from the phosphine being broken up. The amount of each dopant species (i.e., its percentage relative to the total ion beam) can be adjusted by adjusting the conditions of the plasma, such as the power used. In this respect, a user can manage the break-up of the dopant and can tailor it as desired (e.g., 80% P^+, 10% P^{++}, 5% P^{+++}, 3% P_2^+, etc.). Each species is implanted into the wafer at a different depth because their energies are different. This feature can be used for formation of multiple atomic profiles that net into the desired shape ideal for the fabrication.

The use of the grid plates of the present invention with limited openings between the chamber region that contains the plasma and the chamber region that contains the substrate ensures effective differentially-pumped regions. In the plasma region, vacuum has to be controlled in order to allow for the formation of the plasma and minimize any other unwanted species presence. However, a differentially-pumped substrate chamber is also critical because the vacuum can be somewhat variable due to the impact of the

substrate surface out-gassing and the load-locking burst of gas. This grid assembly also provides protection against free radicals and other potential airborne hydrocarbons that can affect the surface of the substrate adversely.

The formation of the beam-lets and their subsequent expansion, as a result of natural space charge beam expansion, can be utilized to provide lateral selective region implantation or homogenous implantation. As previously discussed, for the selective implant, the target substrate and a defining grid or a shadow mask can be positioned very close to the third grid plate or in a similar position as for the homogenous implant. The minimum distance for the substrate's proximity to the grid is determined by the voltage holding and applied potential to the grid assembly. The role of the beam-defining shadow mask is to ensure fidelity in the positioning of the implanted region. This mask can be used for improving the alignment of the mask to the substrate, and thus, ensures a higher degree of overlap between selective implanted regions and the subsequent metal grid lines that are screen or jet ink printed on the solar cell.

Such conformal doping of substrate can be utilized to form both homogenous and selective emitter regions through use of a mask and other unique selective doping techniques. At the same time, the dopant profile can be tailored to provide independent surface concentration, shape of the profile and the junction depth, through DC voltage, exposure time, and substrate motion underneath the beam and plasma components adjustments. Furthermore, by the use of the dopant stoichiometric ratio and ratio of molecular radicals present in the plasma, the dopant profile can be further enhanced. This method does not preclude the utilization of the pulsing of the substrate and possible substrate back surface antenna or substrate movement to provide the lateral positioning advantages required for selective implantations.

The system of the present invention can be configured independently of the substrate size. Furthermore, as long as uniformity of plasma is conserved, multiple pieces of substrate can be implanted simultaneously, thereby allowing productivity well in excess of 1000+ wph.

Additionally, the present invention can provide a non-line-of-sight implantation method, and thus, is able to dope areas that are constricted, such as the textured surfaces of multi-grade metallurgical silicon that may have hillocks and re-entrant features on the surface. Doping such areas is critical, as absence of doping may cause metal shunting. Pulsing of the target substrate can be employed to direct the ions these constricted areas.

The implantation system of the present invention provides unique capabilities for solar cell applications. In order to meet the productivity demand of the solar cell industry, multiple-piece simultaneous homogenous implantation can be employed, followed by a masked and selective implantation. However, such implantations can be in any order. For a typical four piece substrate of 156×156 mm pseudo-square, with a total area of 0.25 m^2, such a system preferably comprises a chamber with a dimension of 0.4 min height by 1.2 m in width. This allows for plasma and grid overflow regions to ensure uniformity of implantation on the substrate. Such a system can be used in conjunction with a multi-stage differentially-pumped non-load locked arrangement, as previously discussed, whereby the substrate can be transported on a conveyor or other transport mechanism from an atmospheric side to a vacuum side, and vice versa, which simplifies the whole system and reduces the material cost.

The system of the present invention is expected to generate average ion current density of at least 0.5 mA/cm^2 at 90 kV of high voltage bias, which is derived from the following equation:

$$I_P = \frac{D + Ze(1+\gamma_{SE})A}{f\Delta t + T} \times a \times b$$

where, assuming a typical plasma system:

D=dose [cm-2]

f=pulse frequency [s]

Δt=pulse duration [μs]

I_p=peak current [A]

T=implantation time [s]

Z=charge state

e=electron charge [A-s]

γSE=secondary electron emission coeff

A=surface area [cm^{-2}]

a=stoichiometric ratio of dopant

b=molecular ratio of radical in plasma

One example provides a gas of PH_3, a dose of E16 cm^{-2}, a stoichiometric ratio of dopant of 0.25, and a molecular ratio of radical in plasma of 0.3.

The system of the present invention can be used for multiple species, so as to avoid any cross contamination of dopants. Additionally, in some embodiments, the internal walls of the chamber is clad with appropriate material so as to minimize the potential of metallic contamination, and other unwanted contamination, and ease of cleaning, servicing and replacement. Furthermore, as previously discussed, a confining field, such as an electric field, can be added to the internal chamber walls in order to limit the interactions of the plasma or the ions from the surrounding materials. In some embodiments, the ion beam can be skewed and a unique field can be applied so as to only allow the passage of the required species to the target substrate.

The profile of the solar cell can further be tailored by the present invention's use of plasma content adjustment, which can be achieved through the special use of micro-wave or RF coupling with plasma so as to modify the plasma intensity and temperature, and thus control the break-up of the constituents, as previously discussed. This adjustment can affect stoichiometric ratio of dopant and the molecular ratio of radicals present in the plasma. For example, for the use of solid phosphorus, its various components such as P^+, P^{++}, P^{+++}, P_2^+, P_3^+, P_5^+, etc. can be used to ensure that near surface tailoring is achieved. This adjustment can be used for other dopants as well, such as n-type boron.

Another benefit of the plasma implant technology of the present invention is the prevalence of hydrogen, if an appropriate source of the dopant is used, such as PH_3 or B_2H_6. The hydrogen will simultaneously implanted with the other dopant, and at higher energies, which will help provide auto-gettering and surface passivation effects that are unique and useful for poorer quality solar cell materials.

A variable energy accelerating the plasma, either in distinct steps or as a continuum, can also be employed to form the required profile and manage to generate an independent surface concentration, atomic profile shaping and junction depths. This could be distinct and in known steps, or can be as continuum to appropriate pauses at required energy to contrast the desired profiles.

The average distributed power density provided by the present invention lends itself to implantation of very thin wafers (e.g., less than 20 microns) whether they are inde-

pendent or mounted on other substrates, and ensures that thicker wafers remain at a temperature of less than 100° C. throughout the process. The distributed power density also enables the processing of non-silicon-based substrates such as CdTe, CIGS, and a-Si thin-film substrate, which require low substrate temperature operation. Wafer cooling and heating may be necessary, in particular as the wafer thickness is reduced, which can be provided in the form of typical backside water cooling or gas cooling or other similar methods.

Such distributed power density allows utilization of various hard masking (e.g., resist) materials that may not have been considered before with diffusion (high temperature) and directed implant (high instantaneous power density).

Another advantage of the present invention is that no subsequent diffusion is required, and thus, lower temperature anneal as low as 500° C. can provide enough activation and damage anneal that can be used for fabrication of a PV cell. Plasma grid implantation, due to its high productivity, can provide higher doses. Therefore, if only a portion of the dopant is activated, the desired resistivity and performance can still be achieved. Auto-annealing also may be employed, where the power of the beam is used to heat the substrate to such a desired temperature so that self-annealing can take place. Furthermore, balancing the elevated temperature of the substrate, masks, and grid assembly can be of major benefit in the general operation, control and metrology of the system.

Utilizing the high productivity of the unique plasma grid implant system, an integrated module of SiNx deposition in conjuction with junction-doping applications can be also achieved without breaking the vacuum. The plasma grid implantation system of the present invention can be used to achieve surface passivation. The difference between implantation and deposition is the energy of the ions. The lower the energy, the more the ions stay on the surface. The present invention enables the formation of a passivation layer, such as a nitride film, on the surface of the wafer through the use of a very low energy implant. The technique currently used is a chemical process. The present invention allows for the application of a passivation layer simply by bleeding a passivation gas, such as silicon or nitrogen, into the plasma region of the chamber.

FIG. **14** illustrates a process flow diagram of one embodiment of a method **1400** of ion implantation in accordance with the principles of the present invention. At step **1410**, a plasma is provided within a plasma region of a chamber. A first grid plate and a second grid plate are disposed within the chamber. At step **1420**, the second grid plate is negatively biased. The second grid plate comprises a plurality of apertures and is disposed in a first position. At step **1430**, the first grid plate is positively biased. The first grid plate comprises a plurality of apertures and is disposed in a first position. Although FIG. **14** shows the step of the second grid plate being negatively biased before the step of the first grid plate being positively biased, in some embodiments, the biasing of the first grid plate is initiated before or simultaneously with the biasing of the second grid plate. At step **1440**, ions from the plasma in the plasma region are flown through the apertures in the positively-biased first grid plate. At step **1450**, at least a portion of the ions that flowed through the apertures in the positively-biased first grid plate are flown through the apertures in the negatively-biased second grid plate. At step **1460**, a substrate is implanted with at least a portion of the ions that flowed through the apertures in the negatively-biased second grid plate, with the substrate being disposed in a first position. The process can then be repeated with the positioning of the grid plates and/or the substrate being adjusted in order to achieve both homogeneous and selective ion implantation.

FIG. **15** illustrates a process flow diagram of another embodiment of a method **1500** of ion implantation in accordance with the principles of the present invention. At step **1510**, a plasma is provided within a plasma region of a chamber. At step **1520**, a grid assembly is provided comprising a plurality of grid plates. Each grid plate comprises a plurality of apertures. At step **1530**, a first set of ions from the plasma in the plasma region is flown through the apertures in each of the grid plates in the grid assembly while each of the grid plates is in a first position. At step **1540**, a substrate is homogeneously implanted with at least a portion of the first set of ions that flowed through the apertures in the grid plates while the substrate is supported in a first position by a substrate holder, thereby forming a single laterally-homogeneous ion implantation across the substrate from a combination of the first set of ions that have passed through different apertures of the same grid plate. At step **1550**, the position of the substrate or at least one of the grid plates is adjusted to a second position. At step **1560**, a second set of ions from the plasma in the plasma region is flown through the apertures in each of the grid plates in the grid assembly subsequent to the adjustment to the second position. At step **1570**, the substrate is selectively implanted with at least a portion of the second set of ions that flowed through the apertures in the grid plates subsequent to the adjustment to the second position, thereby forming a plurality of laterally spaced-apart ion implantations on the substrate from a portion of the second set of ions that have passed through different apertures of the same grid plate.

FIG. **16** illustrates a process flow diagram of yet another embodiment of a method **1600** of ion implantation in accordance with the principles of the present invention. At step **1610**, a single type of dopant material is provided to a plasma generator. At step **1620**, the plasma generator breaks up the single type of dopant material into a plurality of dopant species. At step **1630**, a substrate is implanted with the plurality of dopant species.

In some embodiments, a combination of different types of dopant material is used to implant different pluralities of dopant species. In some embodiments, the different types of dopant material can be provided in precursor form as gasses, liquids, solids, or any combination thereof.

The present invention has been described in terms of specific embodiments incorporating details to facilitate the understanding of principles of construction and operation of the invention. Such reference herein to specific embodiments and details thereof is not intended to limit the scope of the claims appended hereto. It will be readily apparent to one skilled in the art that other various modifications may be made in the embodiment chosen for illustration without departing from the spirit and scope of the invention as defined by the claims.

The invention claimed is:

1. A method for forming solar cells in an implant chamber having a plasma region and implant region defined by a grid assembly, comprising:

differentially pumping the plasma region and the implant region of an implant chamber;

supplying doping gas into the plasma region;

sustaining plasma in the plasma region;

loading wafers onto a conveyor system and placing physical masks in contact with the wafers;

operating the conveyor to deliver the wafer with the masks to the implant region through a plurality of

increased vacuum stages, each with increasing level of vacuum leading to the implant region, wherein the implant region having highest level of vacuum, and to remove the wafers from the implant region through a plurality of reduced vacuum stages, each with a decreasing level of vacuum leading away from the implant region;

positioning the wafers with the masks underneath the grid assembly; and,

implanting the ions through the masks onto unmasked regions of the wafers.

2. The method of claim **1**, further comprising adjusting conditions of the plasma to control percentage of each ion species relative to the total ion beam.

3. The method of claim **1**, further comprising forming multiple atomic profiles by implanting multiple ion species at different energies.

4. The method of claim **1**, comprising implanting multiple wafers simultaneously.

5. The method of claim **1**, comprising forming an inter-digitated alternate doping regions of n-type and p-type on the wafers.

6. The method of claim **1**, comprising simultaneously implanting hydrogen and dopant ions.

7. The method of claim **1**, further comprising heating the wafers with the ion beam to cause self-annealing of the wafer.

* * * * *