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Chistyakov

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(54) **METHODS AND APPARATUS FOR GENERATING HIGH-DENSITY PLASMA**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 748 days.

This patent is subject to a terminal disclaimer.

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C23C 14/35 (2006.01)
C23C 16/00 (2006.01)

(52) **U.S. Cl.** ..... **204/192.12**; 204/298.08; 204/298.06; 204/298.19; 315/111.21; 315/111.41; 118/723 R; 118/723 E

(58) **Field of Classification Search** ..... 204/192.12, 204/298.08, 298.06, 298.19; 118/723 R, 118/723 E; 315/111.21, 111.41
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,588,490	A	5/1986	Cuomo et al.	204/298
4,953,174	A	8/1990	Eldridge et al.	372/87
5,015,493	A	5/1991	Gruen	427/38
5,041,760	A *	8/1991	Koloc	315/111.41
5,083,061	A	1/1992	Koshiishi et al.	315/111.81
5,247,531	A	9/1993	Muller-Horshe	372/38
5,286,360	A	2/1994	Szcyrbowski et al.	204/298.08
5,433,258	A	7/1995	Barnes et al.	
5,696,428	A	12/1997	Pasch	
5,718,813	A	2/1998	Drummond et al.	204/192.12
5,728,278	A	3/1998	Okamura et al.	204/298.11
5,733,418	A	3/1998	Hershcovitch et al.	204/192.11
5,795,452	A	8/1998	Kinoshita et al.	204/298.37
5,916,455	A	6/1999	Kumagai	
5,993,761	A *	11/1999	Czernichowski et al.	423/210

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0 650 183 A1 4/1995

(Continued)

OTHER PUBLICATIONS

Booth, et al., The Transition From Symmetric To Asymmetric Discharges In Pulsed 13.56 MHz Capacitively Coupled Plasmas, J. Appl. Phys., Jul. 15, 1997, pp. 552-560, vol. 82, No. 2, American Institute of Physics.

(Continued)

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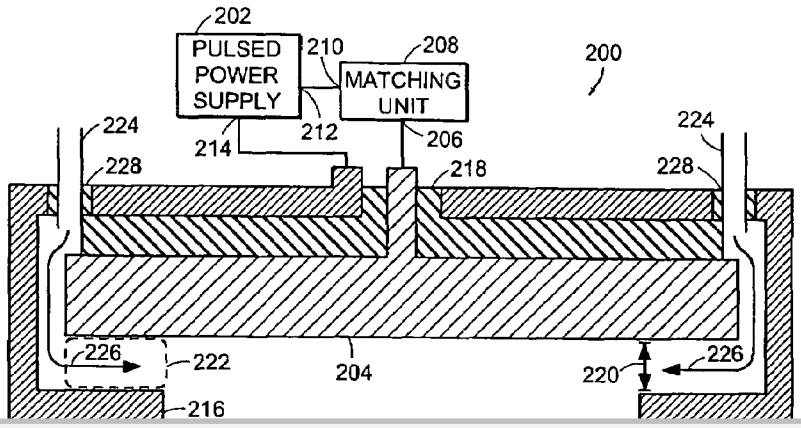
(74) *Attorney, Agent, or Firm*—Kurt Rauschenbach; Rauschenbach Patent Law Group, LLC

(57) **ABSTRACT**

Methods and apparatus for generating a strongly-ionized plasma are described. An apparatus for generating a strongly-ionized plasma according to the present invention includes an anode and a cathode that is positioned adjacent to the anode to form a gap there between. An ionization source generates a weakly-ionized plasma proximate to the cathode. A power supply produces an electric field in the gap between the anode and the cathode. The electric field generates excited atoms in the weakly-ionized plasma and generates secondary electrons from the cathode. The secondary electrons ionize the excited atoms, thereby creating the strongly-ionized plasma.

33 Claims, 13 Drawing Sheets



U.S. PATENT DOCUMENTS

6,057,244	A	5/2000	Hausmann et al.	438/706
6,238,537	B1	5/2001	Kahn et al.	204/598.04
6,296,742	B1	10/2001	Kouznetsov	204/192.12
6,361,667	B1	3/2002	Kobayashi et al.	204/298.11
6,413,382	B1	7/2002	Wang et al.	204/192.12
6,413,383	B1	7/2002	Chiang et al.	204/192.13
6,432,260	B1	8/2002	Mahoney et al.	
6,436,251	B2	8/2002	Gopalraja et al.	204/298.12
6,451,703	B1	9/2002	Liu et al.	438/710
6,471,833	B2	10/2002	Kumar et al.	204/192.37
6,488,825	B1 *	12/2002	Hilliard	204/298.06
2002/0019139	A1	2/2002	Zhang et al.	438/714
2002/0114897	A1	8/2002	Sumiya et al.	427/569
2003/0006008	A1	1/2003	Horioka et al.	156/345.46

FOREIGN PATENT DOCUMENTS

WO	WO 98/40532	9/1998
WO	WO 01/98553	12/2001
WO	WO 01/98553 A1	12/2001

OTHER PUBLICATIONS

Bunshah, et al., Deposition Technologies For Films And Coatings, pp. 178-183, Noyes Publications, Park Ridge, New Jersey.
Daugherty, et al., Attachment-Dominated Electron-Beam-Ionized Discharges, Applied Physics Letters, May 15, 1976, pp. 581-583, vol. 28, No. 10, American Institute of Physics.
Goto, et al., Dual Excitation Reactive Ion Etcher For Low Energy Plasma Processing, J. Vac. Sci. Technol. A., Sep./Oct. 1992, pp. 3048-3054, vol. 10, No. 5, American Vacuum Society.
Kouznetsov, et al., A Novel Pulsed Magnetron Sputter Technique Utilizing Very High Target Power Densities, Surface and Coatings Technology, 1999, pp. 290-293, vol. 122, Elsevier Science S.A.
Lindquist, et al., High Selectivity Plasma Etching Of Silicone Dioxide With A Dual Frequency 27/2 MHz Capacitive RF Discharge.
Macak, Reactive Sputter Deposition Process of Al203 And Characterization Of A Novel High Plasma Density Pulsed Magnetron Discharge, Linkoping Studies In Science And Technology, pp. 1-2.
Macak, et al., Ionized Sputter Deposition Using An Extremely High Plasma Density Pulsed Magnetron Discharge, J. Vac. Sci. Technol. A., Jul./Aug. 2000, pp. 1533-1537, vol. 18, No. 4., American Vacuum Society.
Mozgrin, et al., High-Current Low-Pressure Quasi-Stationary Discharge In A Magnetic Field: Experimental Research, Plasma Physics Reports, 1995, pp. 400-409, vol. 21, No. 5.
Rossnagel, et al., Induced Drift Currents In Circular Planar Magnetrons, J. Vac. Sci. Technol. A., Jan./Feb. 1987, pp. 88-91, vol. 5, No. 1, American Vacuum Society.
Sheridan, et al., Electron Velocity Distribution Functions In A Sputtering Magnetron Discharge For The EXB Direction, J. Vac. Sci. Technol. A., Jul./Aug. 1998, pp. 2173-2176, vol. 16, No. 4, American Vacuum Society.
Steinbruchel, A Simple Formula For Low-Energy Sputtering Yields, Applied Physics A., 1985, pp. 37-42, vol. 36, Springer-Verlag.
Encyclopedia Of Low Temperature Plasma p. 119, vol. 3.
Encyclopedia Of Low Temperature Plasma p. 123, vol. 3.
Chistyakov, Roman, High Power Pulsed Magnetron Sputtering, U.S. Appl. No. 10/065,277, filed Sep. 30, 2002.
Chistyakov, Roman, High Power Pulsed Magnetically Enhanced Plasma Processing, U.S. Appl. No. 10/065,551, filed Oct. 29, 2002.
Booth, et al., The Transition From Symmetric To Asymmetric Discharges In Pulsed 13.56 MHz Capacity Coupled Plasmas, J. Appl. Phys., Jul. 15, 1997, pp. 552-560, vol. 82 (2), American Institute of Physics.
Bunshah, et al., Deposition Technologies For Films And Coatings, Materials Science Series, pp. 176-183, Noyes Publications, Park Ridge, New Jersey.
Daugherty, et al., Attachment-Dominated Electron-Beam-Ionized Discharges, Applied Science Letters, May 15, 1976, vol. 28, No. 10, American Institute of Physics.
Goto, et al., Dual Excitation Reactive Ion Etcher for Low Energy Plasma Processing, J. Vac. Sci. Technol. A, Sep./Oct. 1992, pp. 3048-3054, vol. 10, No. 5, American Vacuum Society.
Kouznetsov, et al., A Novel Pulsed Magnetron Sputter Technique Utilizing Very High Target Power Densities, Surface & Coatings Technology, pp. 290-293, Elsevier Sciences S.A.
Lindquist, et al., High Selectivity Plasma Etching Of Silicon Dioxide With A Dual Frequency 27/2 MHz Capacitive RF Discharge.
Macak, Reactive Sputter Deposition Process of Al2O3 and Characterization Of A Novel High Plasma Density Pulsed Magnetron Discharge, Linkoping Studies In Science And Technology, 1999, pp. 1-2, Sweden.
Macak, et al., Ionized Sputter Deposition Using An Extremely High Plasma Density Pulsed Magnetron Discharge, J. Vac. Sci. Technol. A., Jul./Aug. 2000, pp. 1533-1537, vol. 18, No. 4, American Vacuum Society.
Mozgrin, et al., High-Current Low-Pressure Quasi-Stationary Discharge In A Magnetic Field: Experimental Research, Plasma Physics Reports, 1995, pp. 400-409, vol. 21, No. 5, Mozgrin, Feitsov, Khodachenko.
Chistyakov, Roman, High-Power Pulsed Magnetron Sputtering, U.S. Appl. No. 10/065,277, filed Sep. 30, 2002.
Chistyakov, Roman, High-Power Pulsed Magnetically Enhanced Plasma Processing, U.S. Appl. No. 10/065,551, filed Oct. 30, 2002.
Chistyakov, High-Power Pulsed Magnetron Sputtering, U.S. Appl. No. 10/065,277, filed Sep. 30, 2002.
Chistyakov, High-Power Pulsed Magnetically Enhanced Plasma Processing, U.S. Appl. No. 10/065,551, filed Oct. 29, 2002.
Chistyakov, Roman, Method And Apparatus For Generating High-Density Plasma, U.S. Appl. No. 10/065,629, filed Nov. 4, 2002.
Chistyakov, Roman, High Deposition Rate Sputtering, U.S. Appl. No. 10/065,739, filed Nov. 14, 2002.
Chistyakov, Roman, Plasma Generation Using Multi-Step Ionization, U.S. Appl. No. 10/249,202, filed Mar. 21, 2003.
Chistyakov, Roman, High-Density Plasma Source, U.S. Appl. No. 10/249,595, filed Apr. 22, 2003.
Chistyakov, Roman, Generation Of Uniformly Distributed Plasma, U.S. Appl. No. 10/249,773, filed May 6, 2003.
Chistyakov, Roman, High-Density Plasma Source Using Excited Atoms, U.S. Appl. No. 10/249,844, filed May 12, 2003.
Chistyakov, Roman, Plasma Source With Segmented Cathode, U.S. Appl. No. 60/481,671, filed Nov. 19, 2003.
Chistyakov, Roman, Methods And Apparatus For Generating Strongly-Ionized Plasmas With Ionizational Instabilities, U.S. Appl. No. 10/708,281, filed Feb. 22, 2004.
Chistyakov, Roman, Plasma Source With Segmented Cathode, U.S. Appl. No. 10/710,946, filed Aug. 13, 2004.
"Notification Of Transmittal Of The International Search Report Or The Declaration" For PCT/US03/34483, Apr. 8, 2004, 5 pages, The International Searching Authority/EPO, Rijswijk, The Netherlands.
US 5,863,392, 01/1999, Drummond et al. (withdrawn)

* cited by examiner

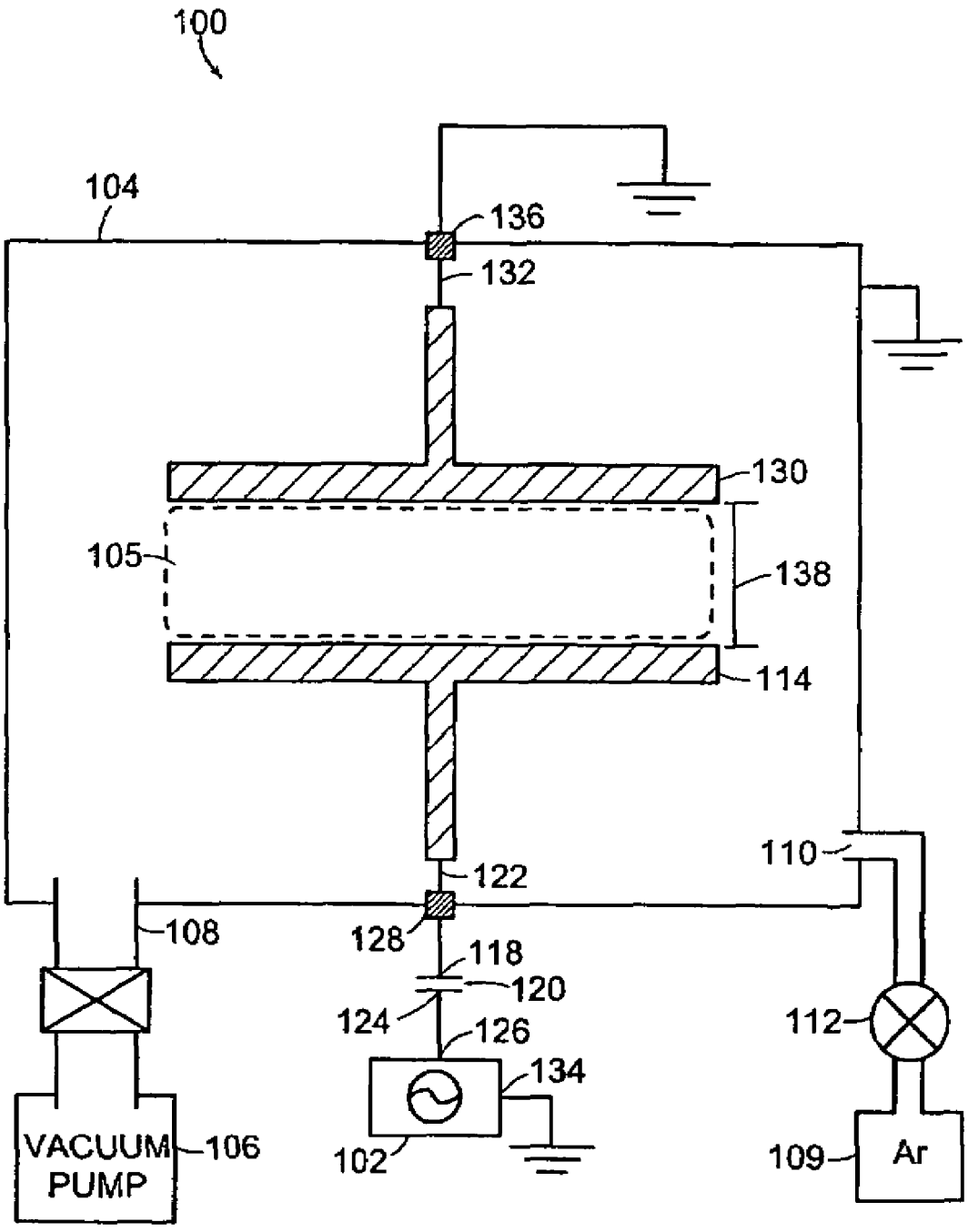


FIG. 1
PRIOR ART

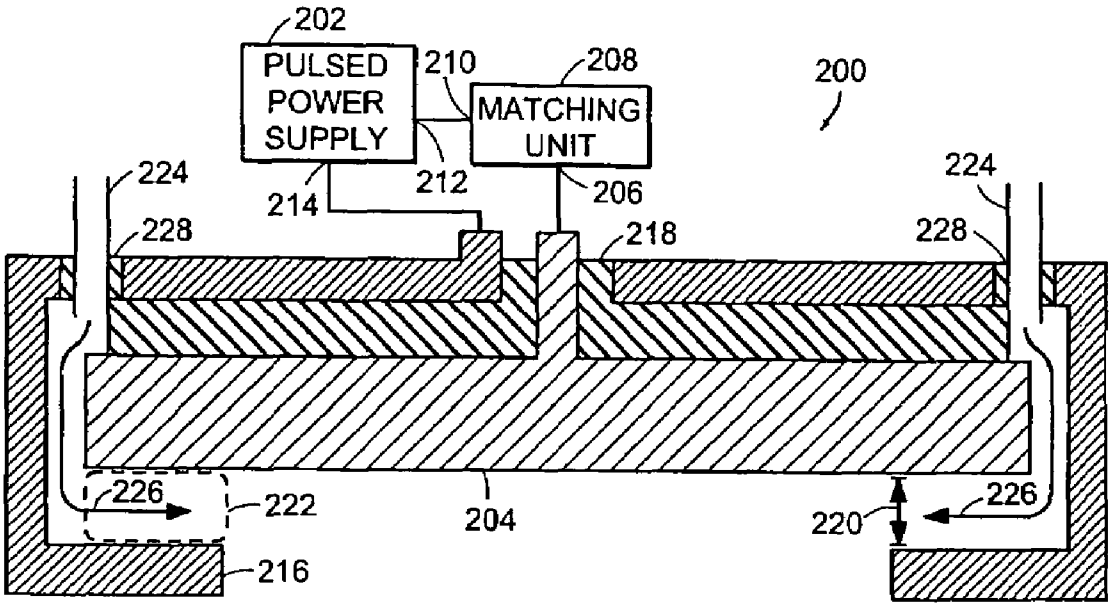


FIG. 2A

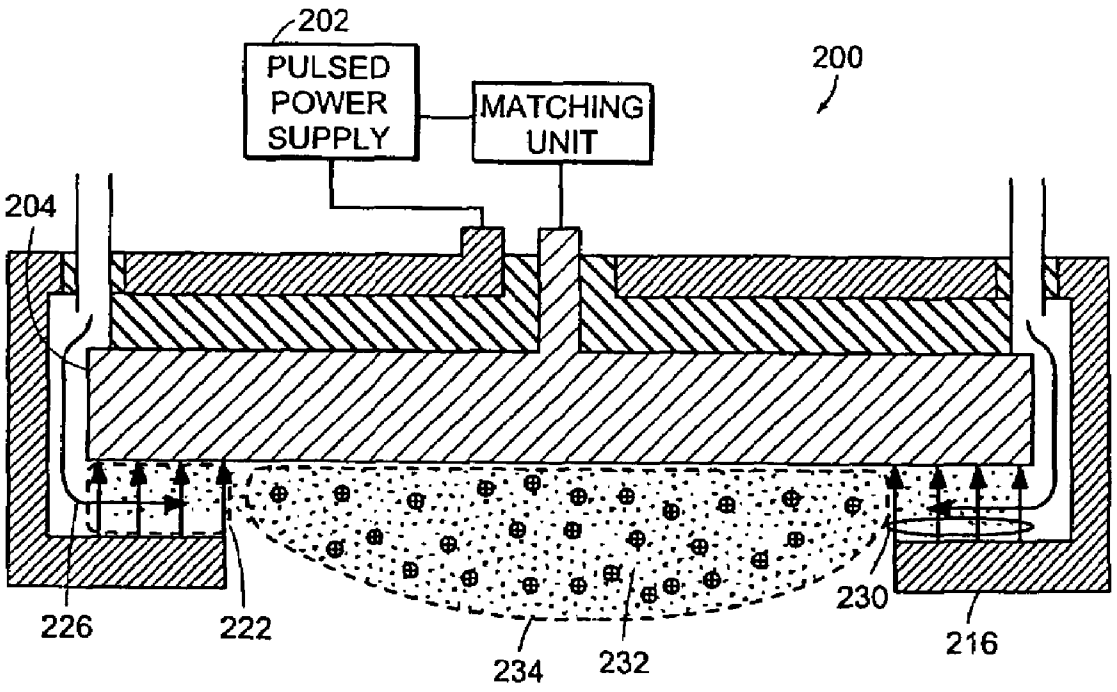


FIG. 2B

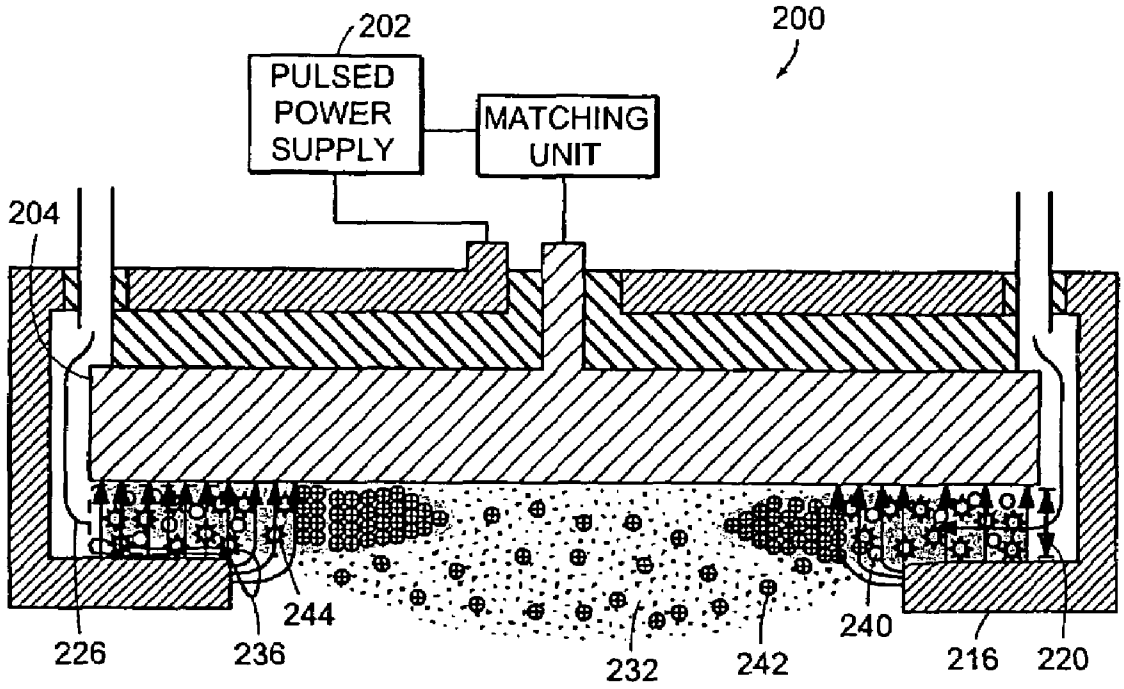


FIG. 2C

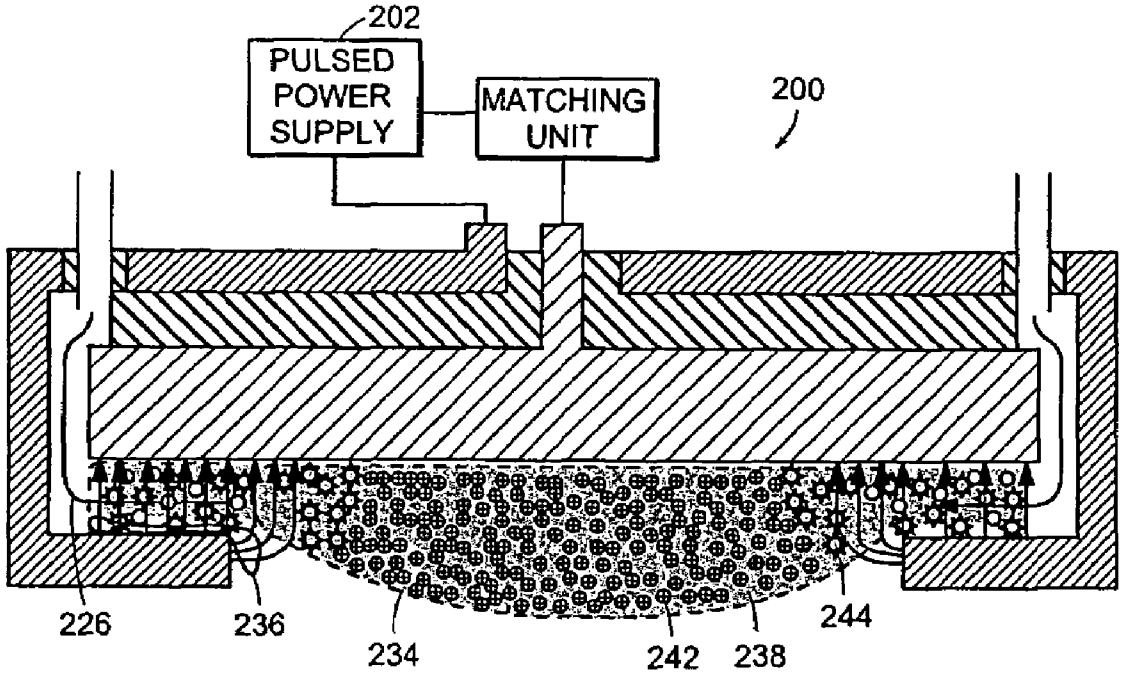


FIG. 2D

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