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Chistyakov

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(54) **METHODS AND APPARATUS FOR GENERATING STRONGLY-IONIZED PLASMAS WITH IONIZATIONAL INSTABILITIES**

4,458,180 A * 7/1984 Sohval et al. 315/111.81
4,588,490 A 5/1986 Cuomo et al.
4,931,169 A 6/1990 Scherer et al.

(Continued)

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FOREIGN PATENT DOCUMENTS

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DE 3700633 C1 5/1998

(Continued)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 882 days.

OTHER PUBLICATIONS

This patent is subject to a terminal disclaimer.

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.

(Continued)

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(52) **U.S. Cl.** **315/111.21**; 315/111.41; 315/111.71

(58) **Field of Classification Search** 315/111.21–111.91; 216/67, 71; 118/723 VE, 118/723 R; 156/345.33; 204/192.12, 192.1, 204/298.08

See application file for complete search history.

(57) **ABSTRACT**

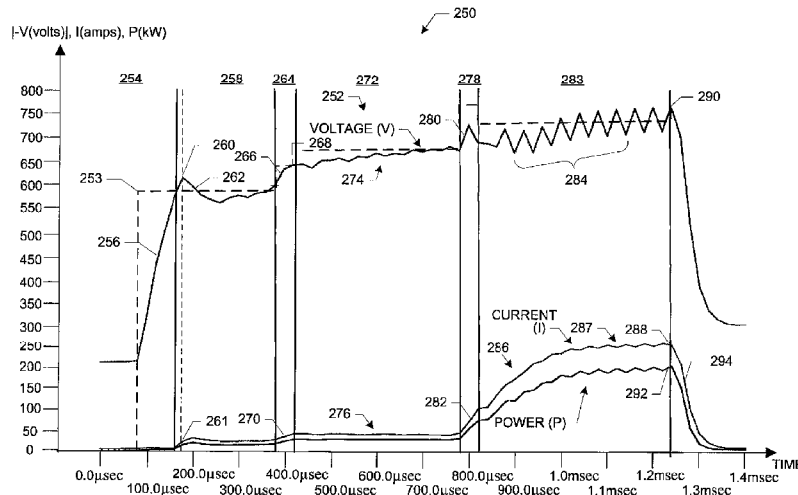
Methods and apparatus for generating strongly-ionized plasmas are disclosed. A strongly-ionized plasma generator according to one embodiment includes a chamber for confining a feed gas. An anode and a cathode assembly are positioned inside the chamber. A pulsed power supply is electrically connected between the anode and the cathode assembly. The pulsed power supply generates a multi-stage voltage pulse that includes a low-power stage with a first peak voltage having a magnitude and a rise time that is sufficient to generate a weakly-ionized plasma from the feed gas. The multi-stage voltage pulse also includes a transient stage with a second peak voltage having a magnitude and a rise time that is sufficient to shift an electron energy distribution in the weakly-ionized plasma to higher energies that increase an ionization rate which results in a rapid increase in electron density and a formation of a strongly-ionized plasma.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,104,345 A 9/1963 Wilcox et al.

20 Claims, 16 Drawing Sheets



U.S. PATENT DOCUMENTS

| | | | | |
|--------------|------|---------|----------------------|------------|
| 5,002,631 | A | 3/1991 | Giapis et al. | |
| 5,015,493 | A | 5/1991 | Gruen | |
| 5,303,139 | A | 4/1994 | Mark | |
| 5,476,693 | A * | 12/1995 | Lee et al. | 427/577 |
| 5,537,005 | A * | 7/1996 | Goebel et al. | 315/111.81 |
| 5,565,247 | A | 10/1996 | Suzuki et al. | |
| 5,616,224 | A | 4/1997 | Boiling | |
| 5,718,813 | A | 2/1998 | Drummond et al. | |
| 5,728,278 | A | 3/1998 | Okamura et al. | |
| 5,828,176 | A * | 10/1998 | Goebel | 315/111.41 |
| 5,844,195 | A | 12/1998 | Fairbairn et al. | |
| 6,124,675 | A | 9/2000 | Bertrand et al. | |
| 6,197,165 | B1 | 3/2001 | Drewery et al. | |
| 6,222,321 | B1 | 4/2001 | Scholl et al. | |
| 6,254,745 | B1 | 7/2001 | Vukovic | |
| 6,296,742 | B1 | 10/2001 | Kouznetsov | |
| 6,327,163 | B1 | 12/2001 | Petr | |
| 6,342,132 | B1 | 1/2002 | Rossnagel | |
| 6,355,992 | B1 | 3/2002 | Via | |
| 6,359,424 | B2 | 3/2002 | Iida et al. | |
| 6,413,382 | B1 | 7/2002 | Wang et al. | |
| 6,416,634 | B1 | 7/2002 | Mostovoy et al. | |
| 6,521,099 | B1 | 2/2003 | Drummond et al. | |
| 6,621,674 | B1 | 9/2003 | Zahringer et al. | |
| 6,633,017 | B1 | 10/2003 | Drummond et al. | |
| 6,735,099 | B2 | 5/2004 | Mark | |
| 6,805,779 | B2 | 10/2004 | Chistyakov | |
| 6,806,651 | B1 | 10/2004 | Chistyakov | |
| 6,806,652 | B1 | 10/2004 | Chistyakov | |
| 6,808,607 | B2 | 10/2004 | Christie | |
| 6,853,142 | B2 | 2/2005 | Chistyakov | |
| 6,896,773 | B2 | 5/2005 | Chistyakov | |
| 6,896,775 | B2 | 5/2005 | Chistyakov | |
| 6,903,511 | B2 | 6/2005 | Chistyakov | |
| 2002/0008480 | A1 * | 1/2002 | Yamazaki et al. | 315/111.21 |
| 2004/0020760 | A1 | 2/2004 | Kouznetsov | |
| 2004/0060813 | A1 | 4/2004 | Chistyakov | |
| 2004/0086434 | A1 | 5/2004 | Gadgil et al. | |
| 2004/0094411 | A1 | 5/2004 | Chistyakov | |
| 2004/0112735 | A1 | 6/2004 | Saigal et al. | |
| 2004/0124077 | A1 | 7/2004 | Christie | |
| 2005/0092596 | A1 | 5/2005 | Kouznetsov | |
| 2005/0103620 | A1 | 5/2005 | Chistyakov | |
| 2005/0109607 | A1 | 5/2005 | Ehiasarian et al. | |
| 2005/0173239 | A1 | 8/2005 | Somekh et al. | |
| 2005/0184669 | A1 | 8/2005 | Chistyakov | |
| 2005/0247554 | A1 | 11/2005 | Saigal et al. | |
| 2009/0263966 | A1 | 10/2009 | Weichart et al. | |

FOREIGN PATENT DOCUMENTS

| | | | |
|----|-------------|----|---------|
| EP | 1046726 | A2 | 10/2000 |
| EP | 1 260 603 | A1 | 11/2002 |
| EP | 1046726 | B1 | 7/2009 |
| JP | 2004 010979 | A | 1/2001 |
| RU | 2 029 411 | C1 | 2/1995 |
| RU | 2 058 429 | C1 | 4/1996 |
| WO | 98/40532 | | 9/1998 |
| WO | 02/103078 | A1 | 12/2002 |

OTHER PUBLICATIONS

Steinbruchel, A Simple Formula for Low-Energy Sputtering Yields, *Applied Physics A*, 1985, pp. 37-42, vol. 36, Springer, Verlag.

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.

Fajans, et al., Bifurcations in Elliptical, Asymmetric Non-Neutral

Dekoven, et al., Carbon Thin Film Deposition Using High Power Pulsed Magnetron Sputtering, 46th Annual Technical Conference Proceedings, 2003, pp. 158-165, Society of Vacuum Coaters.

Stark, et al., Electron Heating in Atmospheric Pressure Glow Discharges, *Journal of Applied Physics*, Apr. 2001, p. 3568, vol. 89, No. 7, American Institute of Physics.

Gudmundsson, et al., Evolution of the Electron Energy Distribution and Plasma Parameters in a Pulsed Magnetron Discharge, *Applied Physics Letters*, May 28, 2001, pp. 3427-3429, American Institute of Physics.

Mozgrin, et al., High-Current Low-Pressure Quasi-Stationary Discharge in a Magnetic Field: Experimental Research, *Plasma Physics Reports*, 1995, vol. 21, No. 5, pp. 400-409, Interperiodica Publishing.

Garrigues, et al., Hybrid and Particle-In-Cell Models of a Stationary Plasma Thruster, *Plasma Sources Sci. Technol.*, 2000, pp. 219-226, vol. 9, IOP Publishing Ltd., UK.

Kudryavtsev, et al., Ionization Relaxation in a Plasma Produced by a Pulsed Inert-Gas Discharge, *Sov. Phys. Tech. Phys.*, Jan. 1983, pp. 30-35, vol. 28, No. 1, American Institute of Physics.

Biberman, et al., Low-Temperature Plasmas with Nonequilibrium Ionization, *Sov. Phys. Usp.*, Jun. 1979, pp. 411-432, vol. 22, No. 6.

Thornton, Magnetron Sputtering: Basic Physics and Application to Cylindrical Magnetrons, *J. Vac. Sci. Technol. Mar./Apr. 1978*, pp. 171-177, vol. 15, No. 2.

Helmerson, Metallization by Pulsed High-Power Sputtering, [online]. [retrieved on Nov. 21, 2003]. Retrieved from WWW.inf.liu.se/thinprogram/projects/p2.html.

Pisarev, Modification of the Surface of Perforated Polymer MF-4SK in Low-Pressure, High Current Quasi-Stable Discharge Plasma in Magnetic Field, [online]. [retrieved on Dec. 30, 2003]. Retrieved from WWW.tech-db.ru/lstc/db/prs.nsf/we/0624.

Gudmundsson, et al., Observation of Ion-Acoustic Solitons in a Pulsed Magnetron Sputtering Discharge, 56th-Gaseous Electronics Conference-2003, Oct. 24, 2003, pp. 1-14.

Matossian, et al., Operating Characteristics of a 100kV, 100kW Plasma Ion Implantation Facility, *Surface Coatings & Technology*, 1996, pp. 92-97, vol. 85.

Fajans, et al., Second Harmonic Autoresonant Control of the I=1 Diocotron Mode in Pure-Electron Plasmas, *Physical Review E*, Sep. 2000, pp. 4131-4136, vol. 62, No. 3.

J.T. Gudmundsson, et al., Spatial and Temporal Behavior of the Plasma Parameters in a Pulsed Magnetron Discharge, *Surface & Coatings Technology*, 2002, pp. 249-256, vol. 161, Elsevier Science.

Biberman, et al., Chapter Eight: Transient Nonequilibrium Plasmas, Kinetics of Nonequilibrium Low Temperature Plasmas, 1987, pp. 321, 360-372, Plenum Publishing Corporation, New York, USA.

Gudmundsson, et al., Observation of Solitons in a Pulsed Magnetron Sputtering Discharge [online]. [retrieved on Dec. 8, 2003]. Retrieved from WWW.eps.org/aps/meet/GEC03/baps/abs/s300.html.

The State of the Art in Pulsed High Power [online]. [retrieved on Jul. 15, 2002]. Retrieved from WWW.physiqueindustrie.com/_pulse_power.html.

Encyclopedia of Low Temperature Plasma, Editor V.E. Fortov, 2000, vol. 3, p. 123

Encyclopedia of Low Temperature Plasma, Editor V.E. Fortov, 2000, vol. 3, p. 119.

Hart, et al., Growth of Soliton-like Structures From Normal Modes and Particle Loss From a Nonneutral Plasma, [online]. Non-Neutral Plasmas, Archibald/Cochran, 3rd Floor, Tower, Nov. 7, 1995.

Vladimirov, V., Voltage-Current Characteristics of a Gas Magnetron in the Case of Intense Cathode Sputtering, *Sov. J. Plasma Phys.*, Jan.-Feb. 1981, pp. 114-118, vol. 7, No. 1.

Lutsenko, E.I., Instability Mechanisms in a High-Current Straight Discharge at a Low Gas Pressure, *Sov. J. Plasma Phys.*, Jan.-Feb. 1984, pp. 87-95, vol. 10, No. 1.

"Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration" for PCT/US08/004644, Aug. 21, 2008, 14 pages, the International Searching Authority/EPO, Rijswijk, The Netherlands.

"Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration" for PCT/US08/004644, Aug. 21, 2008, 14 pages, the International Searching Authority/EPO, Rijswijk, The Netherlands.

- "Office Action" for U.S. Appl. No. 10/065,277, Jan. 15, 2004, 12 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,277, Aug. 30, 2004, 14 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,277, May 27, 2005, 13 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,277, Jan. 11, 2006, 15 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,277, Jul. 18, 2006, 6 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,629, Oct. 7, 2003, 11 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,739, Feb. 18, 2004, 14 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/065,739, May 20, 2004, 14 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/249,202, Feb. 11, 2004, 6 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/249,595, Apr. 22, 2004, 5 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/249,774, Aug. 27, 2004, 6 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/249,844, Apr. 23, 2004, 5 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/553,893, Mar. 7, 2008, 6 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/708,281, May 18, 2005, 15 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/708,281, Dec. 20, 2005, 14 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/710,946, Nov. 16, 2007, 7 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/710,946, Feb. 21, 2008, 18 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/710,946, Apr. 10, 2009, 18 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/897,257, Mar. 27, 2008, 13 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/897,257, Jan. 14, 2009, 7 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 10/949,427, Apr. 21, 2006, 6 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/091,814, Jul. 14, 2008, 19 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/130,315, Jul. 3, 2008, 10 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/162,824, Apr. 28, 2008, 8 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/162,824, Jan. 23, 2009, 10 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/162,824, May 18, 2009, 9 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/183,463, Oct. 24, 2008, 7 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/376,036, Jul. 25, 2007, 7 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 11/608,833, Mar. 11, 2009, 8 pages, The USPTO, US.
- "Office Action" for U.S. Appl. No. 12/245,193, Apr. 2, 2009, 4 pages, The USPTO, US.
- "Notification Concerning Transmittal of International Preliminary Report on Patentability (Chapter I of the Patent Cooperation Treaty)" for PCT/US2008/004644, Nov. 5, 2009, 10 pgs., The International Bureau of WIPO, Geneva, Switzerland.
- "Notification Concerning Transmittal of International Preliminary Report on Patentability (Chapter I of the Patent Cooperation Treaty)" for PCT/US2008/004605, Oct. 29, 2009, 9 pgs., The International Bureau of WIPO, Geneva, Switzerland.
- Bugaev, S. P., et al., Investigation of a High-Current Pulsed Magnetron Discharge Initiated in the Low-Pressure Diffuse Arc Discharge, *Thin Solid Films*, 2001, pp. 16-26, vol. 389, Elsevier Science B.V.
- Bugaev, S. P., et al., Ion-Assisted Pulsed Magnetron Sputtering Deposition of Ta-C Films, *Thin Solid Films*, 2001, pp. 16-26, vol. 389, Elsevier Science B.V.
- D' Couto, G. C., et al., In Situ Physical Vapor Deposition of Ionized Ti and TiN Thin Films Using Hollow Cathode Magnetron Plasma Source, *J. Vac. Sci. Technol. B*, Jan./Feb. 2001, pp. 244-249, vol. 19, No. 1, American Vacuum Society.
- Ehiasarian, A. P., et al., High Power Pulsed Magnetron Sputtered CrNx Films, *Dunnschicht-/Plasmatechnik*, 2003, pp. 1480-1487.
- Ehiasarian, A. P., et al., Influence of High Power Densities on the Composition of Pulsed Magnetron Plasmas, *Vacuum*, 2002, pp. 147-154, vol. 65, Elsevier Science Ltd.
- Gudmundsson, J. T. et al., Spatial and Temporal Behavior of the Plasma Parameters in a Pulsed Magnetron Discharge, *Surface and Coatings Technology*, 2002, pp. 249-256, vol. 161, Elsevier Science B.V.
- Gudmundsson, J. T. et al., Evolution of the Electron Energy Distribution and Plasma Parameters in a Pulsed Magnetron Discharge, *Applied Physics Letters*, May 28, 2001, pp. 3427-3429, vol. 78, No. 22, American Institute of Physics.
- Hopwood, J., Ionized Physical Vapor Deposition of Integrated Circuit Interconnects, *Physics of Plasmas*, May 1998, pp. 1624-1631, vol. 5, No. 5, American Institute of Physics.
- Kervilshvii, N. A., et al., Low-Pressure Discharge in Crossed Fields (E,H) in a Magnetron and Penning Cell, *Sov. Phys. Tech. Phys.*, 1976, pp. 1591-1596, vol. 20, No. 12, American Institute of Physics.
- Korneev, V.V., Electric Fields in a Nonequilibrium Inhomogeneous Weakly Ionized Plasma, *Sov. J. Plasma Phys.*, Nov.-Dec. 1978, pp. 784-785, vol. 4, No. 6, American Institute of Physics.
- Lebedev, S. Ya., et al., Cathode Sputtering Under the Action of Cesium Ions, *Soviet Physics—Technical Physics*, Dec. 1964, pp. 854-856, vol. 9, No. 6.
- Oks, E. M., et al., Plasma Emission Properties of a Superdense Glow Discharge Excited in Crossed Electric and Magnetic Fields, *Sov. Phys. Tech. Phys.*, Jun. 1991, pp. 712-714, vol. 36, No. 6, American Institute of Physics.
- Rasmussen, C. E., et al., Ionization and Current Growth in an E X B Discharge, *Plasma Physics*, 1969, pp. 183-195, vol. 11, Pergamon Press, Northern Ireland.
- Redhead, P. A., Instabilities in Crossed-Field Discharges At Low Pressures, *Vacuum*, 1988, pp. 901-906, vol. 38, No. 8-10, Pergamon Press, Great Britain.
- Steinbruchel, Ch., A Simple Formula for Low-Energy Sputtering Yields, *Appl. Phys. A.*, 1985, pp. 37-42, vol. 36, Springer-Verlag.
- Westwood, W. D., The Current-Voltage Characteristic of Magnetron Sputtering Systems, *J. Appl. Phys.*, Dec. 1983, pp. 6841-6846, vol. 54, No. 12, American Institute of Physics.
- "Office Action" for European Patent Application No. 03-781-508.1-1226, Apr. 1, 2008, 5 pages, the European Patent Office.
- "Response to Office Action" for European Patent Application No. 03-781-508.1-1226, Oct. 13, 2008, 13 pages.
- "Supplement to Response to Office Action" for European Patent Application No. 03-781-508.1-1226, Oct. 23, 2008, 4 pages.
- "Office Action" for European Patent Application No. 03-781-508.1-1226, Apr. 7, 2010, 3 pages, the European Patent Office.
- "Office Action" for European Patent Application No. 03-779-387.4-1215, Oct. 10, 2007, 4 pages, the European Patent Office.
- "Response to Office Action" for European Patent Application No. 03-779-387.4-1215, Apr. 21, 2008, 15 pages.
- "Summons to Oral Proceedings" for European Patent Application No. 03-779-387.4-1215, Dec. 15, 2009, 6 pages, the European Patent Office.
- "Office Action" for European Patent Application No. 03-776-584.9-1226, Sep. 18, 2008, 6 pages, the European Patent Office.
- "Response to Office Action" for European Patent Application No. 03-776-584.9-1226, Jul. 23, 2009, 12 pages.
- "Office Action" for European Patent Application No. 04-749-844.9-2208, Jan. 28, 2009, 2 pages, the European Patent Office.
- "Office Action" for European Patent Application No. 04-750-797.5-2208, Oct. 16, 2008, 5 pages, the European Patent Office.

US 7,808,184 B2

Page 4

“Response to Office Action” for European Patent Application No. 04-716-928.9-2208, Jul. 24, 2007, 20 pages.

“Office Action” for European Patent Application No. 04-810-268.5.2208, Apr. 23, 2009, 3 pages, the European Patent Office.

“Response to Office Action” for European Patent Application No. 04-810-268.5.2208, May 29, 2009, 2 pages.

“Office Action” for European Patent Application No. 05-723-194.6-1226, Nov. 5, 2009, 6 pages, the European Patent Office.

“Office Action” for European Patent Application No. 05-800-880.6-1226, Jan. 25, 2010, 3 pages, the European Patent Office.

“Office Action” for Japanese Patent Application No. 2004-551595, Aug. 24, 2009, 2 pages, the Japanese Patent Office.

“Response to Office Action” for Japanese Patent Application No. 2004-551595, Feb. 18, 2010, 3 pages.

* cited by examiner

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