



US007808184B2

(12) **United States Patent**  
**Chistyakov**

(10) **Patent No.:** **US 7,808,184 B2**  
(45) **Date of Patent:** **\*Oct. 5, 2010**

(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)

(75) Inventor: **Roman Chistyakov**, Andover, MA (US)

FOREIGN PATENT DOCUMENTS

(73) Assignee: **Zond, Inc.**, Mansfield, MA (US)

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)

(21) Appl. No.: **11/465,574**

Primary Examiner—Douglas W Owens

(22) Filed: **Aug. 18, 2006**

Assistant Examiner—Tung X Le

(65) **Prior Publication Data**

US 2006/0279223 A1 Dec. 14, 2006

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

**Related U.S. Application Data**

(63) Continuation of application No. 10/708,281, filed on Feb. 22, 2004, now Pat. No. 7,095,179.

(51) **Int. Cl.**  
**H05B 31/26** (2006.01)

(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.

(56) **References Cited**

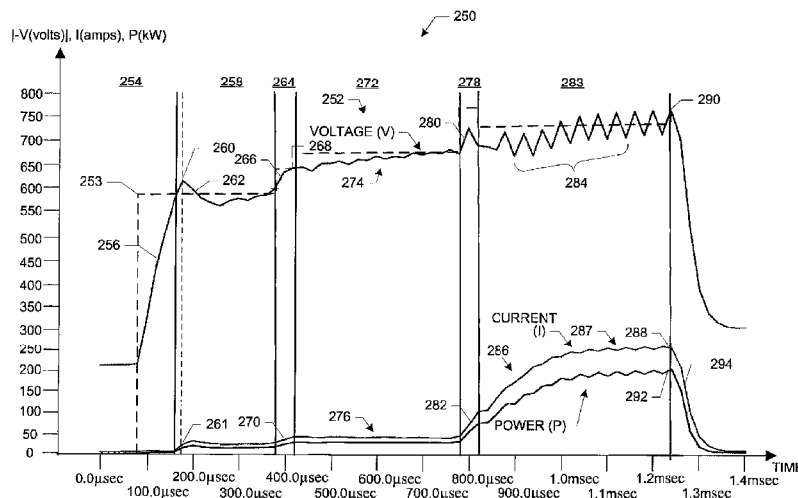
U.S. PATENT DOCUMENTS

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

(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.

**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

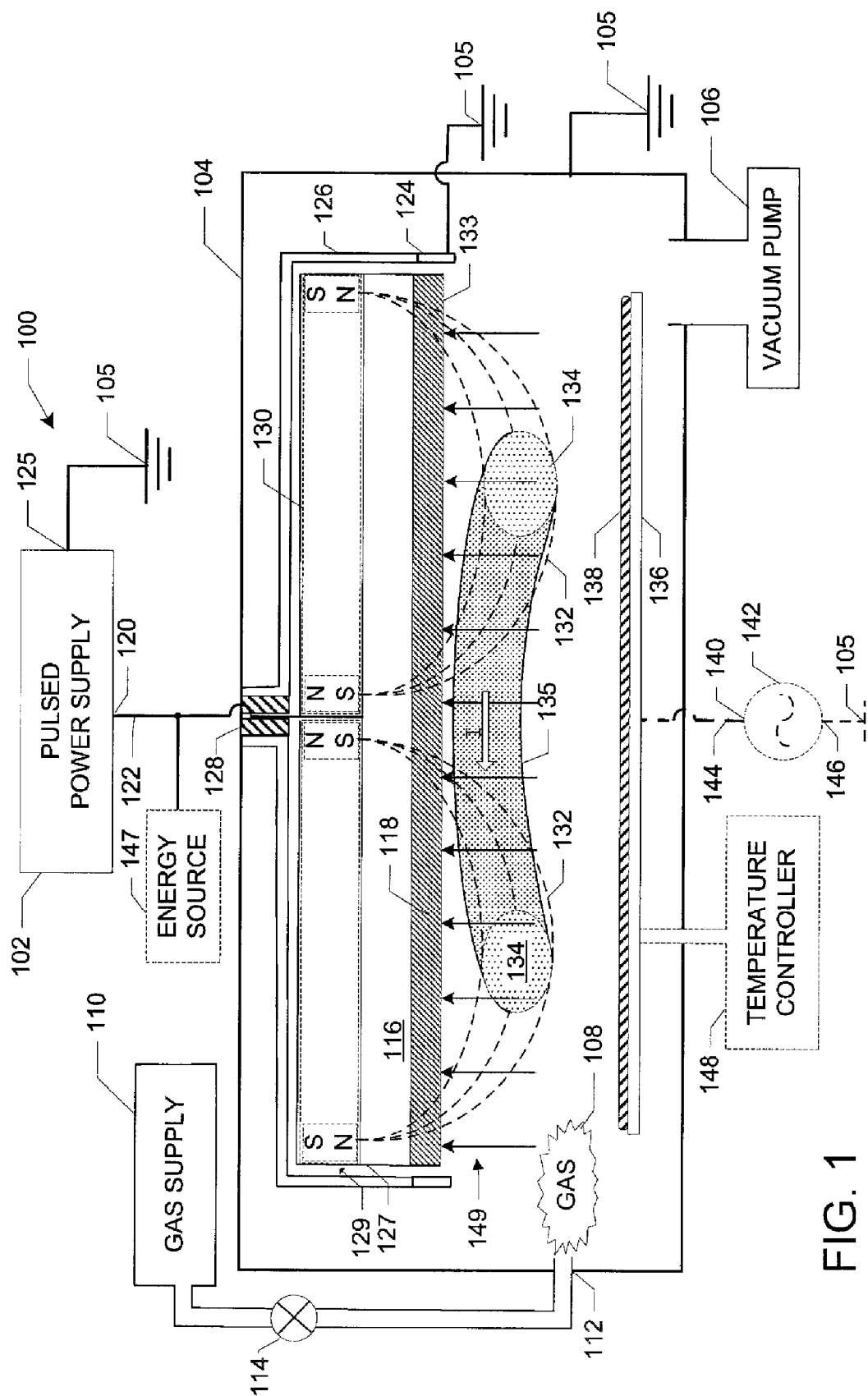


FIG. 1

# Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

## Real-Time Litigation Alerts



Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

## Advanced Docket Research



With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

## Analytics At Your Fingertips



Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

## API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

## LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

## FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

## E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.