Applied Physics 应用物理, 2012, 2, 109-115
http://dx.doi.org/10.12677/app.2012.24019

Research Progress of the Linear Plasma Source Used in the Films Deposition over Large Areas

Xiao Zuo, Longwei Chen*, Yu Wei, Yin Zhao, Yuedong Meng

Applied Plasma Division, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei
Email: lwchen@ipp.ac.cn

Received: May 31st, 2012; revised: Jun. 14th, 2012; accepted: Jul. 1st, 2012

Abstract: The characteristics and application of several kinds of linear plasma sources are introduced. According to the power sources for plasma systems, there are DC, RF, VHF, microwave and dual frequency linear plasma sources, which with a magnet system are called magnetic field enhanced linear plasma sources. Compared with the conventional large scale plasma sources, linear plasma sources take the advantage that they just need to obtain uniform and stable plasma in one dimension. Through the linear plasma array or moving the substrate in horizontal and vertical direction, large scale uniform thin film can be deposited. Recent years, researchers tried to use the magnetic field to confine plasma so as to reduce the recombination loss in plasma and improve the density, uniformity and stability of plasma. The linear plasma sources with the density above 10^{11} cm^{-3}, dis-uniformity below ±5% (L > 1 m), have been applied to fabricate large scale Si_3N_4, SiO_2, intrinsic Si and nano-diamond thin film.

Keywords: Large Scale; Uniformity; Magnetic Field; Linear Plasma Sources

用于大面积薄膜沉积的线形等离子体源研究进展

左　潇，陈龙威*，魏　钰，赵　颖，孟月东

中科院等离子体研究所低温等离子体应用研究室，合肥
Email: lwchen@ipp.ac.cn

收稿日期：2012 年 5 月 31 日；修回日期：2012 年 6 月 14 日；录用日期：2012 年 7 月 1 日

摘　要：本文系统介绍了几种线形等离子体源的特点及其应用，根据激励源的不同分别称为直流、射频、甚高频、微波、双频线形等离子体源，有磁场辅助的称为磁场增强线形等离子体源。与传统的大面积等离子体源不同，线形等离子体源仅需在一维方向实现均匀、稳定的等离子体，采用多个线形结构并排，或者与被镀样品在水平/垂直方向以适当速度运动，即可获得大面积均匀的薄膜沉积。近年来，研究人员采用磁场约束技术，减少带电粒子在器壁的复合损失，进一步提高等离子体的密度、均匀度和稳定性。线形等离子体及磁场增强线形等离子体密度 $>10^{11}$ cm^{-3}，不均匀度 $<$±5% (L > 1 m)，被广泛用于 Si_3N_4、SiO_2、光伏电池硅本征层、纳米金刚石等薄膜的大面积沉积，具有很重要的应用价值和科学意义。

关键词：大面积；均匀；磁场；线形等离子体

1. 引言

随着低温等离子体增强化学气相沉积技术(Plasma Enhanced Chemical Vapor Deposition, PECVD)在大规模集成电路、太阳能薄膜光伏电池、平板显示器、材料表面改性、功能基团接枝及燃料电池离子交换膜等领域应用的迅速发展，人们迫切地需要一种可以产生高沉积/刻蚀速率、大面积均匀及稳定的低温等离子体技术。为了能够获得这种技术，国内外等离子体业界

---

*通讯作者。

专家为此做出不懈的努力。其一，采用更加优越的等离子体放电激励源，如直流激励源[1]，低频(~500 kHz)激励源[2]，射频(~13.56 MHz)激励源[3]，甚高频(~60 MHz)激励源[4]，超高频(~500 MHz)激励源[5]，双频(13.56 MHz + 27.12 MHz 等)激励源[6]，以及微波(~2.45 GHz)激励源[7]等；其二，采用更加优越的放电位型，例如用射频做等离子体激励源，可以采用有电极电容/电感耦合射频放电[8,9]，也可以采用无电极电感耦合放电和螺旋波放电[10,11]等；其三，采用磁场增强/约束放电[11-16]，例如用微波激励源，可以采用发散磁场位型，也可以采用多级磁场位型等；其重要的目的在于获得高密度、大面积均匀稳定的等离子体源。到目前为止，这种技术仍在不断的研究与探索之中(见表 1)。实验结果表明，提高激励源频率利于提高等离子体密度和降低离子能量，进而提高沉积/刻蚀速率、降低离子轰击对薄膜的损伤等。但同时提高激励源频率存在一些问题，例如电极表面驻波(TEM 波)及渐逝波导模式(TE 波)引起的沉积速率不均匀[17]。

近年来，一种线形等离子体源引起了国内外专家广泛的关注[7,20-28]。与传统的大面积(两维方向)和大体积(三维方向)等离子体源不同，线形等离子体源仅需在一维方向上实现均匀、稳定的等离子体，采用多个线形等离子体源并排，或与被镀样品在水平/垂直方向上以适当速度匀速运动，即可实现均匀的大面积薄膜沉积。这种结构大大降低了高性能等离子体沉积薄膜设备的开发难度，同时亦利于实现沉积薄膜的多工序快速连续工作，具有非常高的应用前景和研究价值。鉴于线形等离子体源的优良特性及其现实应用意义，本文就线形等离子体源的研究现状及存在的关键问题进行了较系统的分析和综述。

Table 1. Several kinds of plasma sources and their features
表 1. 等离子体产生类型及特点

等离子体源	等离子体密度(cm^{-3})	长度 L/直径 φ(m)	不均匀度
MWECR[13]	$\sim 10^{11}$	$\varphi \sim 0.3$	±3.8%
线形微波[14]	$\sim 10^{11} \sim 10^{12}$	L > 1	~5%
PDP[15]	$\sim 10^{12}$	L > 0.15	~5%
线形内置 ICP[18]	$\sim 1.5 \times 10^{11}$	L~2	~11%
甚高频[19]	$\sim 1.5 \times 10^{10}$	L~1	~12.5%

2. 线形等离子体源

2.1. 无磁场线形等离子体源

2.1.1. 射频激励源

传统的电容耦合等离子体的密度不利于沉积速率的提高，电感耦合等离子体沉积速率相对较高但其面积难以提高。基于此，研究人员提出一种线形内置式结构产生高密度电感耦合等离子体，天线的结构包括蛇形[29]、(双)梳状[18,22,29-33]、U 形阵列[34-37]等，典型的天线结构如图 1 所示。在 ICP 等离子体源中，射频诱导电场在空间的分布决定了等离子体中的功率分布和离子密度的分布。因此，诱导电场的空间分布决定了等离子体的均匀性。双梳状天线和梳状天线的区别在于，相邻两根天线中的电流方向不同。相关理论模拟和实验发现，双梳状天线结构导致其产生的诱导电场是中凹型分布，而梳状天线产生的诱导电场是中凸型分布；这就使得双梳状天线产生的等离子体密度的均匀性更好，比梳状天线更适用于大面积均匀薄膜沉积/刻蚀处理。但是在相同功率条件下梳状天线在处理室中心处激发的等离子体密度比双梳状天线更高，适于较小面积的处理。

目前，这种结构适用的基片尺寸为 2300 × 2000 mm^2，等离子体密度约 1.27×10^{11}/cm^3，刻蚀不均匀度约 10.8%。为了达到更高的沉积/刻蚀速率或是更好的性能，研究人员采用了其他天线形状或更高频率(VHF)实现高密度大面积均匀线形阵列等离子体源。结果表明，使用这些方法虽然使等离子体密度有所提高，但在大面积均匀性均有所降低。

2.1.2. 微波激励源

线形微波激励源一般具有高沉积/刻蚀速率的优点，虽然提高激励频率可以提高截止等离子体密度，但由于电极表面驻波(TEM 波)及渐逝波导模式(TE 波)现象，等离子体沉积/刻蚀系统难以实现大面积均匀化。线形微波等离子体有效地结合了微波等离子体及线形结构的优点，近年来得到广泛关注[7,20,21,28,38-42]，图 2 和图 3 分别为波导传输结构和同轴传输结构线形微波等离子体。波导传输结构等离子体激励源有较高等离子体密度，同轴型线形微波等离子体源能克服上述缺点，具备应用于大面积薄膜的均匀沉积的可能性。

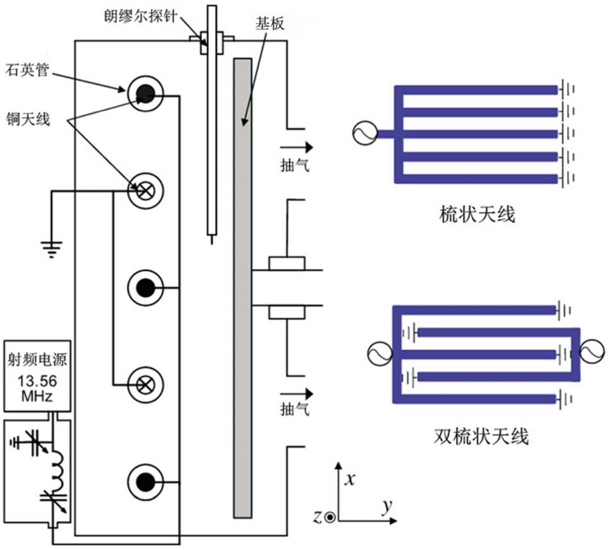


Figure 1. The schematic of internal linear inductively coupled plasma (ICP) sources
图 1. 线形射频内置电感耦合等离子体源结构示意图

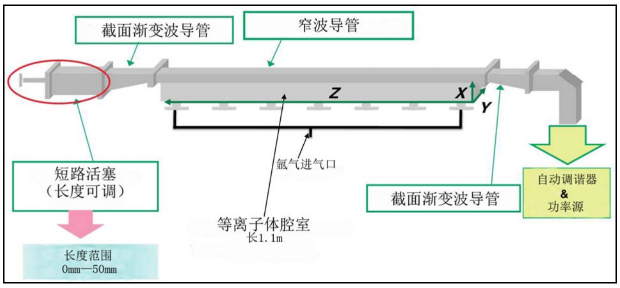


Figure 2. The schematic of linear waveguide conducted microwave plasma sources
图 2. 线形波导传输微波等离子体源结构示意图

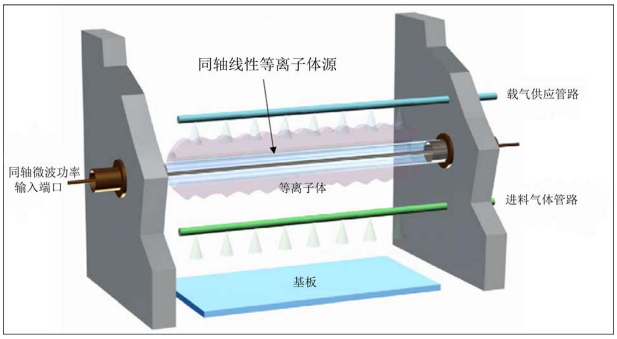


Figure 3. The schematic of coaxial line plasma source
图 3. 线形同轴传输微波等离子体源结构示意图

Yasuhito Kimura 等[20]提出大尺度波导传输微波(2.45 GHz)线形等离子体装置，长度达到 1.1 m，密度约 4 × 1011/cm^3，不均匀度低于 5%。M. Liehr 等[38]提出大面积同轴传输微波线形等离子体源，这种结构利用微波在传输过程中击穿气体形成放电，同时产生的等离子体形成同轴传输外导体导引微波形成同轴传输，这种结构被应用于沉积氮化硅、二氧化硅、纳米金刚石薄膜等[42-44]。

2.1.3. 双频激励源

尽管电感耦合等离子体源(ICP)在大面积表面处理和薄膜沉积上很有应用前景。然而当等离子体源的天线尺寸超过 1 m 时产生的驻波效应，以及由于天线上电压的增加导致与等离子体之间产生容性耦合均会减低等离子体的均匀性。研究者试图通过改变等离子体源天线构造和布局来克服这些问题。

双频等离子体具有高频激励源的高密度以及低频激励源的大面积均匀性，研究人员结合双频激励与线形结构获得大面积、高密度等离子体源[9,45]。图 4 为典型双频线形内置电感耦合等离子体结构示意图。G. H. Gweon 等[9]采用双频激励源(2 MHz/13.56 MHz)获得 880 mm × 660 mm 大面积等离子体源，等离子体密度为 1.6 × 1011/cm^3，不均匀度 6.3%，优于单频(13.56 MHz)的 8.5%。

双频激励源的应用能有效地提高射频等离子体激励源的均匀性。在这种结构下，一方面等离子体在反应室里从激发源到基片台的传播速度增加了；另一方面 2 MHz 射频源的引入与单频激励源(13.56 MHz)在等离子体空间中形成有利于带电粒子在等离子体中扩散的电场位形。

2.2. 磁场增强/约束线形等离子体

磁场的引入能有效地影响电子的运动，一方面电子沿磁力线方向运动平均自由程减小，碰撞的几率增加，因而更容易激发等离子体；另一方面电子沿垂直于磁力线方向的受到约束，向等离子体边缘的扩散运动受到抑制。而由于离子的拉莫尔半径很大，基本上不受磁场的影响。因此不仅在直流放电，即使在高频或微波放电中，磁场的引入是促进等离子体的高密度化、均匀化和低气压化的一种有效手段。

2.2.1. 直流激励源

Volkmar Hopfe 等提出一种新型直流激励等离子体源[46]，用于实现连续、低成本、快速的大气压电弧远程等离子体增强化学气相沉积/刻蚀(linearly extended DC arc discharge，即 LARGE)，图 5 为装置结构示意

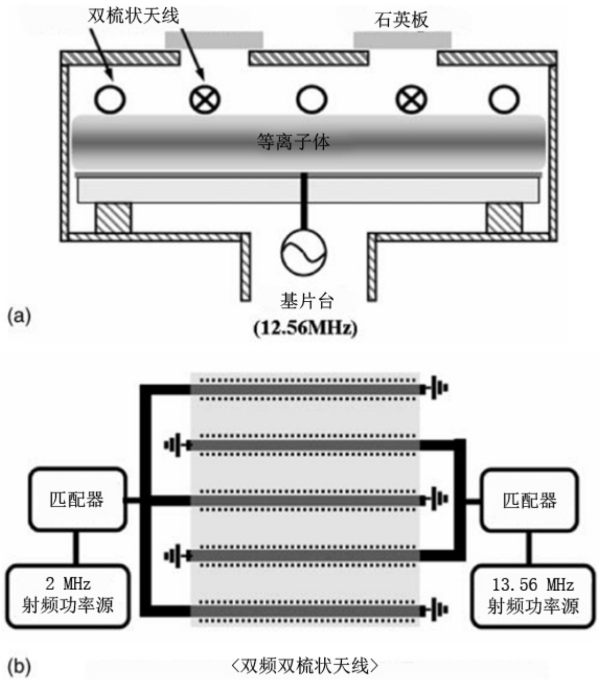
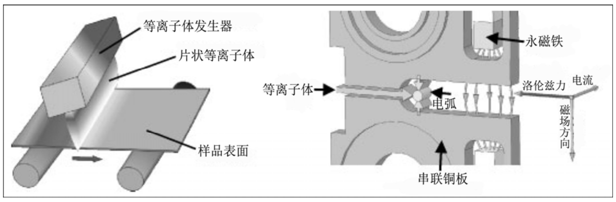


Figure 4. The schematic of dual frequency internal linear inductively coupled plasma sources
图 4. 双频线形内置电感耦合等离子体源结构示意图



(a) (b)

Figure 5. (a) The schematic of flat-panel plasma processing a work piece; (b) The mechanism of horizontal and vertical stability of the arc
图 5. (a) 平板等离子体处理工件示意图；(b) 水平与垂直方向稳定电弧原理示意图

图和等离子体电弧垂直与水平方向的稳定原理示意图。垂直方向通过水冷铜板稳定电弧，而水平方向则是通过磁场与电流相互作用产生的洛仑兹力稳定电弧。该结构能产生高达 104 K 的热等离子体，提供工作长度 450 mm，静态沉积速率 5~50 nm·s^{-1}，动态沉积速率 0.1~1 nm·m^{-1}·s^{-1}。D. Linaschke 等[47]和 I. Dani 等[48]分别采用 LARGE 结构在体硅晶片表面实现管线式等离子体化学刻蚀及大面积晶硅电池表面的等离子体活化等。

这种新型的直流激励等离子体源，相比于传统的大气压化学气相沉积法不仅具有高沉积速率、低成本、便于连续生产等优点外，能实验多种薄膜在廉价衬底(玻璃、不锈钢等)上的大面积均匀制备，对基片温度要求低。

G. Bräuer 等[49]设计一种线形磁控溅射沉积薄膜设备，示意图如图 6 所示。与传统的圆形靶材溅射工作原理相同，但这种线形靶材的长度可以拉长至几乎任意尺寸(如 3.75 m)，通过在上方玻璃基片的运动实现大面积薄膜沉积。

2.2.2. 射频激励源

外置式电感耦合等离子体源由于容性耦合效应导致能量传输效率低导致等离子密度减低以及较高的成本。研究发现通过磁场约束的内置式电感耦合等离子体能提高提高等离子体密度和均匀性。

L. Bardos 等[50]提出射频空心阴极放电线形等离子体源(LAD)，图 7 所示为射频空心阴极放电结构示意图。LAD 系统在两平行板之间形成空心阴极放电，垂直于平行板的磁场能提高电子的反射，同时提高离子对阴极的轰击作用，加热阴极板。将该装置用于沉积 Ti 膜，沉积速率和均匀度达到 150 nm/min 和 3%(长 120 mm)。

LAD 结构产生的等离子体温度一般较高，适宜对高熔点金属薄膜进行沉积。在基于射频电源产生的磁场增强低温等离子体装置结构可归总为两种(图 8 和 9)。图 8 所示为磁场增强线形射频等离子体源示意图，H. Schlemm 等[25]采用该线形等离子体结构实现大面积(1 × 1 m^2)氮化硅薄膜的沉积，沉积速率达到 80 nm/min，不均匀度低于 5%；B. B. Van Aken 等[51]用该装置沉积掺杂非晶硅和微晶硅。

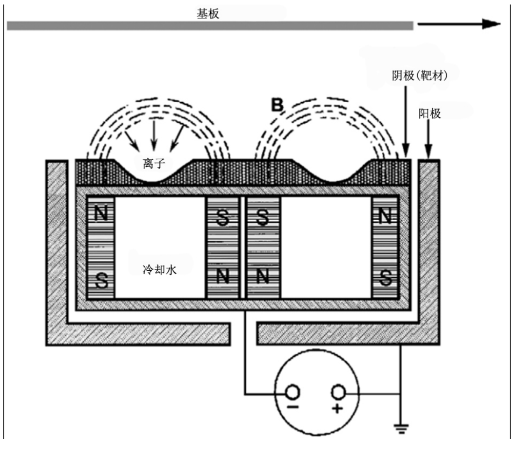


Figure 6. The sectional schematic of linear balanced magnetron sputter
图 6. 线形平衡磁控溅射截面示意图

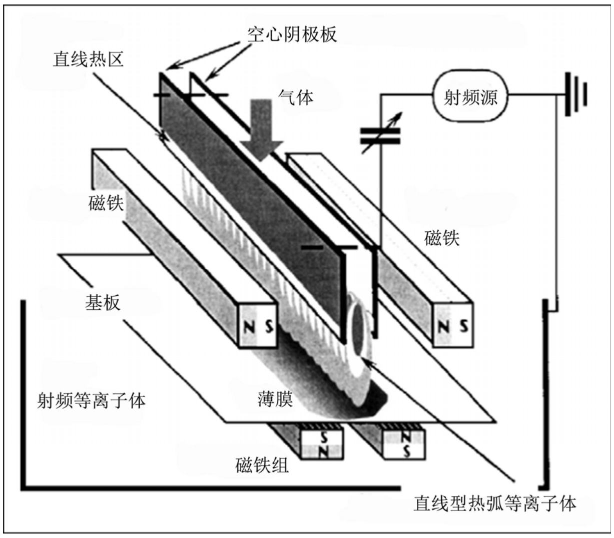


Figure 7. Schematic representation of the linear arc discharge (LAD) system
图 7. LAD 射频空心阴极放电结构示意图

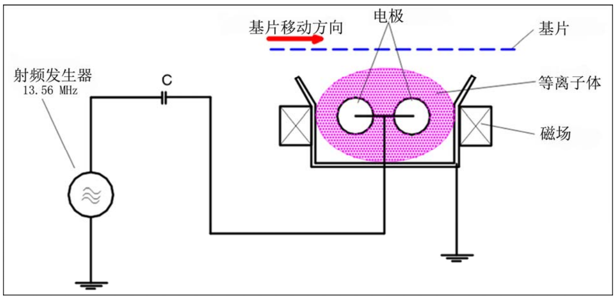
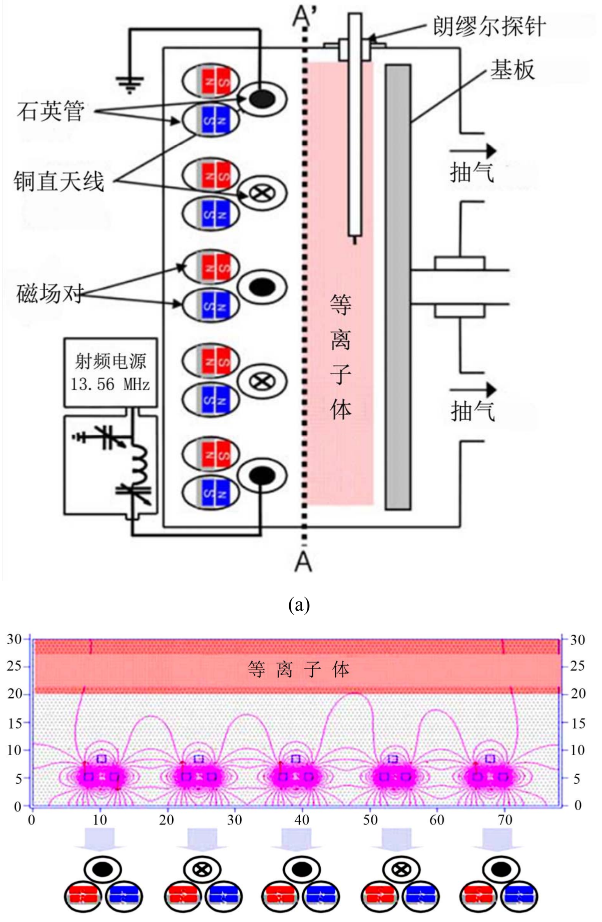


Figure 8. The schematic of magnet enhanced linear plasma sources
图 8. 磁场增强线形射频等离子体源原理示意图

图 9 所示为线形内置式电感耦合等离子体结构示意图及多级磁场阵列磁力线位形。这种结构[16,52-55]通过多个线圈的组合及适当的磁场位形对等离子体的约束作用以获得大面积(~880 × 660 mm^2)、高密度(~3.18 × 10^{11} cm^{-3})、均匀(不均匀度~5%)等离子体源。

这种磁场增强型等离子体激励源放电产生的等离子体密度与无磁场等离子体源的等离子体密度相比提高了 50%，且等离子体的均匀性也有显著的提高；但是相同功率下，电子温度有所降低。

J. Madocks等[15]使用 50~450 kHz电源获得磁场增强Penning放电线形等离子体沉积系统(图 10)，并采用“Roll to Roll”(R2R)结构实现柔性材料基片上连续的薄膜沉积，沉积速率高达 500 nm/min，不均匀度~5% (150 mm)，磁镜位型的磁场极大提高了射频源等离子体沉积系统的性能。



(a)

(b)

Figure 9. (a) The schematic of internal linear inductively coupled plasma (ICP) sources; (b) The schematic of multi-magnetic field array
图 9. (a) 线形内置式电感耦合等离子体结构示意图；(b) 多级磁场阵列磁力线位形

2.2.3. 微波激励源

相比较磁场增强直流、射频线形等离子体源，磁场增强微波激励线形等离子体具有更高的截止密度(2.45 GHz, 7.4 × 1010 cm^{-3})，产生的等离子体将具有更优异的非平衡特性。H. Schlemm 等[14]采用磁场增强线形微波等离子体源(图 11)实现工业级大面积光伏电池氮化硅薄膜的沉积，磁场提高了线形微波等离子体源的等离子体密度、稳定性、均匀度以及工作气压，薄膜面积 20 × 100 cm^2 沉积速率为 150 nm/min，均匀度优于 95%，工作气压 1 Pa~100 Pa，具有极高的应用前景。

3. 结论

线形等离子体源日渐引起国内外专家的广泛关注，其仅需在一维方向实现均匀、稳定的等离子体，

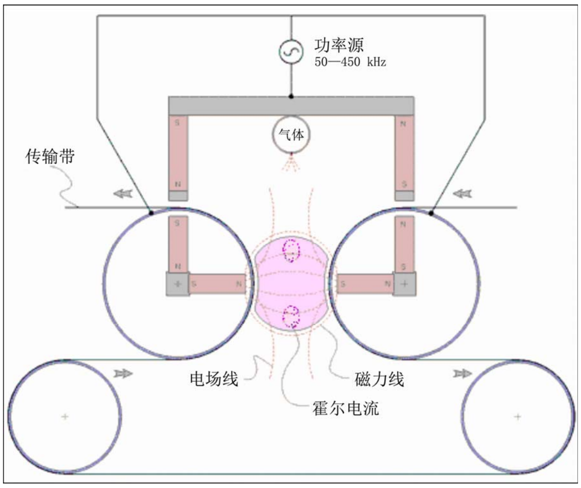


Figure 10. The schematic of roll to roll penning discharging
图 10. R2R 潘宁放电等离子体结构示意图

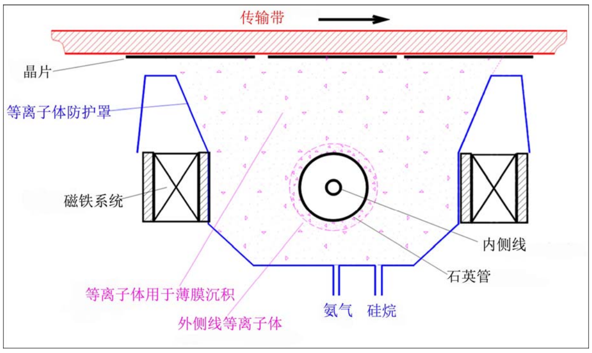


Figure 11. The sectional schematic of magnet enhanced linear microwave plasma sources
图 11. 磁场增强线形微波等离子体截面图

采用多个线形结构并排，或者与被镀样品在水平/垂直方向以适当速度运动，即可获得大面积均匀的薄膜沉积。本文主要论述了目前用于薄膜沉积/刻蚀的几种线形等离子体技术，按其激励源可分为：直流、射频、甚高频、微波、双频等，其目的均在于获得高密度、均匀、稳定的等离子体。磁场(多级场、磁镜场等)能够降低带电粒子在壁面的复合，提高等离子体的密度、均匀度和稳定性，被用于辅助产生射频激励线形等离子体和微波激励线形等离子体，等离子体密度 > 1011 cm^{-3}，不均匀度 < ±5% (L > 1 m)。因其所具有的特点，线形等离子体及磁场增强线形等离子体被广泛用于 Si_3N_4、SiO_2、光伏电池硅本征层、纳米金刚石等薄膜的沉积，具有很重要的应用价值和研究意义。

参考文献 (References)

[1] K. H. Schoenbach, T. Tessnow, F. E. Peterkin and W. W. Byszewski. Microhollow cathode discharges. Applied Physics Letters, 1996, 68(1): 3.

[2] S. Xu, et al. Low-frequency, high-density, inductively coupled plasma sources: Operation and applications. Physics of Plasmas, 2001, 8(5): 2549-2557.

[3] R. Amrani, et al. Optical and structural proprieties of nc-Si:H prepared by argon diluted silane PECVD. Journal of Non-Crystalline Solids, 2012, 358(17): 1978-1982

[4] A. J. Flikweert, et al. Microcrystalline thin-film solar cell deposition on moving substrates using a linear VHF-PECVD reactor and a cross-flow geometry. Journal of Physics D: Applied Physics, 2012, 45(1): Article ID: 015101.

[5] M. Tanjyo, S. Sakai and M. Takahashi. RF ion source for low energy ion implantation—Beam profile control of a large-area ion source using 500-MHz discharge. Surface and Coatings Technology, 2001, 136(1-3): 281-284.

[6] H. Aguas, et al. Large area deposition of polymorphous silicon by plasma enhanced chemical vapor deposition at 27.12 MHz and 13.56 MHz. Japanese Journal of Applied Physics Part 1-Regular Papers Short Notes & Review Papers, 2003, 42(8): 4935-4942.

[7] A. Taylor, et al. Novel high frequency pulsed MW-linear antenna plasma-chemistry: Routes towards large area, low pressure nano-diamond growth. Diamond and Related Materials, 2011, 20(4): 613-615.

[8] R. Rank, T. Wünsche and S. Günther. Magnetically enhanced RF discharges for effective pre-treatment of plastic webs at high speed. Surface and Coatings Technology, 2003, 174-175: 218-221.

[9] G. H. Gweon, et al. Investigation of the plasma uniformity in an internal linear antenna-type inductively coupled plasma source by applying dual frequency. Vacuum, 2010, 84(6): 823-827.

[10] M. Mao, A. Bogaerts. Investigating the plasma chemistry for the synthesis of carbon nanotubes/nanofibres in an inductively coupled plasma enhanced CVD system: The effect of different gas mixtures. Journal of Physics D: Applied Physics, 2010, 43(20): Article ID: 205201.

[11] S. Shinohara, et al. Large-area high-density helicon plasma sources. Plasma Sources Science and Technology, 2010, 19(3): Article ID: 034018.

[12] A. Anders. Plasma and ion sources in large area coating: A review. Surface and Coatings Technology, 2005, 200(5-6): 1893-1906.

[13] W. Miyazawa, et al. A large-area ECR processing plasma. Plasma Sources Science and Technology, 1996, 5(2): 265.

[14] H. Schlemm, et al. Industrial large scale silicon nitride deposition on photovoltaic cells with linear microwave plasma sources. Surface and Coatings Technology, 2003, 174-175: 208-211.

[15] J. Madocks, J. Rewhinkle and L. Barton. Packaging barrier films deposited on PET by PECVD using a new high density plasma source. Materials Science and Engineering: B, 2005, 119(3): 268-273.

[16] K. N. Kim, M. S. Kim and G. Y. Yeom. Effective plasma confinement by applying multipolar magnetic fields in an internal linear inductively coupled plasma system. Applied Physics Letters, 2006, 88(16): Article ID: 161503.

[17] U. Stephan, et al. Problems of power feeding in large area PECVD of amorphous silicon. MRS Proceedings, 1999, 557: 157-162.

[18] J. Lim, et al. Study of internal linear inductively coupled plasma source for ultra large-scale flat panel display processing. Plasma Chemistry and Plasma Processing, 2009, 29(4): 251-259.

[19] D. S. Hwang, et al. Dual comb-type electrodes as a plasma source for very high frequency plasma enhanced chemical vapor deposition. Thin Solid Films, 2010, 518(8): 2124-2127.

[20] Y. Kimura, et al. A new method of line plasma production by microwave in a narrowed rectangular waveguide. Applied Physics Express, 2009, 2(12): 126002-126002-3.

[21] S. Hubner, et al. Investigating a coaxial linear microwave discharges. Journal of Physics D—Applied Physics, 2011, 44(38): Article ID: 385202.

[22] K. N. Kim, et al. Linear inductive antenna design for large area

flat panel display plasma processing. Microelectronic Engineering, 2012, 89: 133-137.

[23] B. B. Van Aken, et al. PECVD deposition of a-Si:H and mu c-Si:H using a linear RF source. San Diego: SPIE, 2007.

[24] T. Zimmermann, et al. Inline deposition of microcrystalline silicon solar cells using a linear plasma source. Physica Status Solidi C—Current Topics in Solid State Physics, 2010, 7(3-4): 1097-1100.

[25] H. Schlemm, M. Fritzsche and D. Roth. Linear radio frequency plasma sources for large scale industrial applications in photovoltaics. Surface & Coatings Technology, 2005, 200(1-4): 958-961.

[26] C. Strobel, et al. Productivity potential of an inline deposition system for amorphous and microcrystalline silicon solar cells. Solar Energy Materials and Solar Cells, 2009, 93(9): 1598-1607.

[27] J. Rudiger, et al. VHF plasma processing for in-line deposition systems. Thin Solid Films, 2003, 427(1-2): 16-20.

[28] M. Kaiser, et al. Linearly extended plasma source for large-scale applications. Surface and Coatings Technology, 1999, 116-119: 552-557.

[29] K. N. Kim, et al. Low-impedance internal linear inductive antenna for large-area flat panel display plasma processing. Applied Physics Letters, 2005, 97(6): Article ID: 063302.

[30] J. H. Lim, et al. Uniformity of internal linear-type inductively coupled plasma source for flat panel display processing. Applied Physics Letters, 2008, 92(5): Article ID: 051504.

[31] K. N. Kim, et al. Scalable internal linear double comb-type inductively coupled plasma source for large area flat panel display processing. Surface and Coatings Technology, 2008, 202(22-23): 5242-5245.

[32] K. N. Kim, S. J. Jung and G. Y. Yeom. Plasma and impedance characteristics of internal linear antennas for flat panel display applications. Thin Solid Films, 2005, 491(1-2): 82-85.

[33] K. N. Kim, et al. Novel internal linear inductively coupled plasma source for flat panel display applications. Japanese Journal of Applied Physics, 2005, 44: 8133.

[34] J. H. Lim, K. N. Kim and G. Y. Yeom. Inductively coupled plasma source using internal multiple U-type antenna for ultra large-area plasma processing. Plasma Processes and Polymers, 2007, 4(S1): S999-S1003.

[35] S. J. Jung, K. N. Kim and G. Y. Yeom. Etching characteristics of multiple U-type internal linear inductively coupled plasma for flat panel display. Surface and Coatings Technology, 2005, 200 (1-4): 780-783.

[36] K. N. Kim, et al. Characteristics of large area inductively coupled plasma using a multiple linear antennas with U-type parallel connection for flat panel display processing. Japanese Journal of Applied Physics, 2006, 45: 8869-8872.

[37] K. N. Kim, S. J. Jung and G. Y. Yeom. Characteristics of inductively coupled plasma with multiple U-type internal antennas for flat panel display applications. Surface and Coatings Technology, 2005, 200(1-4): 784-787.

[38] M. Liehr, M. Dieguez-Campo. Microwave PECVD for large area coating. Surface & Coatings Technology, 2005, 200(1-4): 21-25.

[39] N. Neykova, et al. Novel plasma treatment in linear antenna microwave PECVD system. Vacuum, 2012, 86(6): 603-607.

[40] M. Liehr, S. Wieder and M. Dieguez-Campo. Large area microwave coating technology. Thin Solid Films, 2006, 502(1-2): 9-14.

[41] E. Räuchle. Duo-plasmaline, a surface wave sustained linearly extended discharge. Journal de Physique Archives, 1998, 8(PR7): 99-108.

[42] F. Fendrych, et al. Growth and characterization of nanodiamond layers prepared using the plasma-enhanced linear antennas microwave CVD system. Journal of Physics D: Applied Physics, 2010, 43(37): Article ID: 374018.

[43] 杨志威, 陈立民, 耿春雷, 唐伟忠, 吕反修, 苗晋琦, 赵中琴. 线形同轴耦合式微波等离子体 CVD 法制备金刚石薄膜[J]. 人工晶体学报, 2004, 33: 4.

[44] 唐伟忠, 蒋开云, 耿春雷, 黑立富. 线形微波等离子体 CVD 金刚石薄膜沉积技术[J]. 真空科学与技术学报, 2006, 26: 4.

[45] K. N. Kim, et al. Effect of dual frequency on the plasma characteristics in an internal linear inductively coupled plasma source. Applied Physics Letters, 2006, 89(25): Article ID: 251501.

[46] V. Hopfe, et al. Linear extended ArcJet-CVD—A new PECVD approach for continuous wide area coating under atmospheric pressure. Chemical Vapor Deposition, 2005, 11(11-12): 510-522.

[47] D. Linaschke, et al. In-line plasma-chemical etching of crystalline silicon solar wafers at atmospheric pressure. IEEE Transactions on Plasma Science, 2009, 37(6): 979-984.

[48] I. Dani, et al. Atmospheric-pressure plasmas for solar cell manufacturing. Contributions to Plasma Physics, 2009, 49(9): 662-670.

[49] G. Bräuer. Large area glass coating. Surface and Coatings Technology, 1999, 112(1-3): 358-365.

[50] L. Bardos, et al. Linear arc discharge source for large area plasma processing. Applied Physics Letters, 1997, 70(5): 577.

[51] B. B. Van Aken, et al. Deposition of phosphorus doped a-Si:H and mu c-Si:H using a novel linear RF source. Journal of Non-Crystalline Solids, 2008, 354(19-25): 2392-2396.

[52] Y. J. Lee, et al. Linear internal inductively coupled plasma (ICP) source with magnetic fields for large area processing. Thin Solid Films, 2003, 435(1-2): 275-279.

[53] K. N. Kim, et al. Effects of multipolar magnetic fields on the characteristics of plasma and photoresist etching in an internal linear inductively coupled plasma system. Surface and Coatings Technology, 2004, 177-178: 752-757.

[54] K. N. Kim, J. H. Lim and G. Y. Yeom. Plasma and antenna characteristics of a linearly extended inductively coupled plasma system using multi-polar magnetic field. Thin Solid Films, 2007. 515(12): 5193-5196.

[55] K. N. Kim, et al. Plasma characteristics and antenna electrical characteristics of an internal linear inductively coupled plasma source with a multi-polar magnetic field. Plasma Chemistry and Plasma Processing, 2008, 28(1): 147-158.