VHF-PECVD for *a*-Si:H and *a*-SiN:H Film Deposition

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ABSTRACT

Since 1987, very high frequency (VHF) (30–300 MHz) has been applied to the film deposition process based on theoretical studies on plasma excitation frequency. VHF-plasma enhanced chemical vapor deposition (VHF-PECVD) increases the film deposition rate significantly without deteriorating film quality. Further, the film quality can be controlled via adjustment of the excitation frequency and gas flow rate, which results from the effective dissociation of neutral gases by high-energy electrons. This paper investigates the history of VHF-PECVD for hydrogenated amorphous silicon (*a*-Si:H) and hydrogenated amorphous silicon nitride (*a*-SiN_x:H) film deposition.

Keywords: Very high frequency, Amorphous silicon, Silicon nitride, Thin film deposition, Plasma enhanced chemical vapor deposition

I. Introduction

Hydrogenated amorphous silicon (*a*-Si:H) has been widely used in many industries. The main applications are *a*-Si solar modules, active matrix liquid crystal displays (AM-LCD), and large area imaging sensors [1]. Hydrogenated amorphous silicon nitride (*a*-SiN_x:H) has been also employed in microelectronic and optoelectronic industries to design oxidation masks, passivation layers, gate insulating layers, dielectric layers, and antireflection coatings [2–4].

Plasma-enhanced chemical vapor deposition (PECVD) using radio frequency (RF, 13.56 MHz) and microwave frequency (2.45 GHz) has been widely employed for depositing these films [1,5,6]. However, improvements in the deposition rate to lower cost and improve film quality has always been required. Based on many theoretical studies, very high frequency (VHF, 30–300 MHz) has been used to fabricate *a*-Si:H thin films since 1987 [7–14]. Inspired from these applications, Meiling *et al.* [15] and Takagi *et al.* [16,17] applied VHF to *a*-SiN_x:H film deposition and obtained good results.

In this paper, theoretical and experimental studies on VHF-PECVD are summarized. Section II presents the theoretical background of VHF-PECVD, section III introduces the studies related to *a*-Si:H thin film deposition, section IV presents the investigations conducted on *a*-SiN:H thin film, and section V concludes this paper.

II. Theoretical background

Theoretical studies on the effect of excitation frequency in industrial processing have been conducted previously [6,18–21]. Initial research was started by comparing radio (< 13.56 MHz) and microwave frequencies (2.45 GHz). In 1984, Ferreira and Loureiro developed a model for argon discharge based on the frequency at a low pressure [18]. In 1985, Wertheimer and Moisan [19] observed considerably different film deposition rates and film qualities for radio and microwave frequencies; they showed the transition of electron energy distribution functions (EEDFs) with the excitation frequency based on Ferreira and Loureiro's model (Fig. 1). The EEDFs strongly depend on the parameter ν/ω , where ν is the momentum transfer collision frequency and ω is the excitation angular frequency. If $\nu/\omega \rightarrow \infty$ (low frequency), the EEDF attains a Druyvesteyn shape that rarely has high energy electrons. However, if $\nu/\omega \rightarrow 0$ (microwave case), the EEDF alters to the two-temperature shape that has a large number of high-energy electrons [19].

In 1986, Flamm [20] explained the effect of excitation frequency in plasma processing by using a more intuitive model. Significant



Figure 1. Electron energy distribution function f(u) vs. electron energy u for the argon plasma of constant $\langle u \rangle$ (3.5 eV), but different values of ν/ω : (A) $\nu/\omega \rightarrow \infty$ (LF plasma); (B) $\nu/\omega = 2$; (C) $\nu/\omega = 1.25$; (D) $\nu/\omega \rightarrow 0$ (micro-wave plasma). Reprinted with permission from [7], Copyright 2019, American Vacuum Society.



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changes occur when the excitation frequency exceeds characteristic frequencies related to plasma properties. The VHF range is higher than the electron energy loss frequency (ν_u) and comparable to the momentum transfer collision frequency (ν). ν_u is related to the time-dependency of the EEDF. In the case of $\nu_u \ll \omega,$ such as in the VHF range, the time-dependency of the EEDF becomes negligible. Thus, high-energy electrons can survive for a long time and electronmolecule reactions can occur abundantly. In another study, the parameter ν/ω is explained from a different point of view compared to that in [18,19]. If $\omega \ll \nu$, an electron experiences many collisions during the RF period. In other words, the plasma resistivity is high. However, the electron rarely collides with neutrals during an RF period in the case of $\omega \ll \nu$, which means that the electron hardly obtains energy from the RF field. Therefore, ν/ω determines if the plasma acts inductively or resistively. If $\omega \gg \nu$, the plasma bulk becomes inductive and a stronger electric field is required to apply the same power with a direct current [20]. This strong electric field generates high energy electrons in the EEDF.

In 1990, Beneking [21] explained the change of this electric characteristic based on the excitation frequency in an argon discharge between 10 and 50 MHz by using an impedance analysis. The scaling law of power dissipated in the sheath was defined as $(I/\omega)^{5/2}$, where *I* is the current across the plasma, and ω is the excitation angular frequency. The scaling law indicates that the plasma becomes inductive with an increase in the excitation frequency.

III. Hydrogenated amorphous silicon (*a*-Si:H) thin film deposition

The process of a-Si:H thin film deposition with VHF is described below. Inspired by the theoretical studies, Curtins et al. [7] applied VHF to the a-Si:H thin film deposition process in 1987. The excitation frequency was swept from 25-150 MHz. Figure 2 shows the deposition rate and film properties depending on the excitation frequency. In the range 25-60 MHz, the deposition rate increased with an increase in the excitation frequency and a-Si:H film qualities (the PDS defect density and the optical bandgap) did not change significantly. However, the deposition rate decreased over 70 MHz [7]. Then, VHF was used in the a-Si:H thin film deposition process. Since then, experiments have been conducted by many groups. Oda, Noda, and Matsumura [8] carried out a-Si:H thin film deposition using 144 MHz. Chatham et al. [9] also conducted a-Si:H thin film deposition by sweeping the excitation frequency from 10-110 MHz. Both studies confirmed that VHF improves the film deposition rate without considerable variations in film quality.

The advantages of using VHF in film deposition are high deposition rate and good film quality. Therefore, VHF plasma properties were investigated by many researchers to find the causes of the high deposition rate. The properties of the VHF SiH₄/H₂/He plasma were analyzed by Oda, Noda, and Matsumura by using a Langmuir probe and optical emission spectra (OES) measurement [8]. The electron temperature (T_e) of the VHF plasma was much lower than that of the RF plasma at a low-pressure, ~ 100 mTorr, while the electron density (n_e) was much higher than that of the RF. The high energy tail of the EEDF increased with an increase in the excitation frequency. These results agreed with the theoretical studies. The emission intensity of SiH of the VHF plasma was much stronger than that of the RF plasma in the SiH₄/H₂ discharge [10]. Howling *et al.* [11] showed the correlation



Figure 2. Deposition rate *R*, defect density N_D , and Urbach tail energy E_0 (derived from photothermal deflection spectroscopy data) as functions of plasma excitation frequency *f*. The values of N_D and E_0 refer to samples of an approximately constant thickness $d = 2.3 \pm 0.2 \ \mu m$. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Copyright 2019.

between the deposition rate and the emission intensity of SiH. Though the SiH radical rarely contributes to *a*-Si:H thin film deposition, it is a clear sign that the SiH₄ dissociation is activated and more radical species, which form the film, are created using VHF. The film deposition rate dramatically increases due to the highly dissociated radical species.

In terms of the quality of an *a*-Si:H thin film formed by VHF-PECVD, several researchers conducted experiments to determine the reason for obtaining the good quality film with VHF [8,10,12-14]. Heintze, Zedlitz, and Bauer [14] studied the film parameters by varying the excitation frequency over 40-250 MHz. The film quality maintained a good status in the VHF range. These papers explain the reasons why a good *a*-Si:H film is formed in the VHF range. When VHF is applied, the self-bias on the electrode, plasma potential, and peak-to- peak voltage decreases [10,13,22]. It leads to a drop in the incident ion energy on the film surface. Therefore, the defect caused by ion bombardment is reduced [14].

IV. Hydrogenated amorphous silicon nitride (*a*-SiN_x:H) thin film deposition

VHF-PECVD has been applied to fabricate a-SiN_x:H thin films since 1996 by Takagi *et al.* and Meiling *et al.* [15,16,23]. These studies were conducted to obtain a superior TFT performance with a high deposition rate under a 40 MHz excitation frequency. The film deposited with a high deposition rate still has a good optical bandgap, mobility, internal stress, and high nitrogen content. The TFT performance using VHF-PECVD was applicable to that required for LCD switching devices, which shows the potential of VHF-PECVD for industrial applications [17].

To understand the mechanism of the a-SiN_x:H film deposition, the SiH₄/NH₃/H₂ plasma excited by VHF was investigated. The emission intensity of NH at 40 MHz sharply increases with an increase in the flow rate of SiH₄. The difference between the emission intensities of NH and SiH₄ also increases dramatically at 40 MHz, which means

that the 40 MHz dissociates NH3 gas more effectively than 13.56 MHz [24]. Kim et al. [25,26] studied the characteristics of SiH₄/NH₃/N₂ plasma and a-SiNx:H film using the multiple push-pull plasma (MPPP) with a higher excitation frequency (162 MHz) for suppressing the standing wave problem. The plasma excited by 162 MHz has a lower electron temperature, higher N2 vibrational temperature, and higher $N_{\rm 2}$ dissociation than that excited by 60 MHz. They found that the role of N2 is important to fabricate a good a-SiNx:H film. Hybrid plasma processing using RF (13.56 MHz) and ultrahigh frequency (UHF, 320 MHz) for a-SiN_x:H film fabrication has been researched by Sahu et al. [27-30]. They measured electron energy probability functions (EEPFs) with the variation of the power ratio of RF/UHF. They found that the EEPF alters from the Druyvesteyn to the bi-Maxwellian distribution with an increase in the UHF power ratio. This indicates that the UHF power enhances the generation of the high-energy electrons and the efficiency of N2 dissociation.

In terms of the quality of the a-SiN_x:H film with VHF, Kim *et al.* [25] obtained a high nitrogen composition rate and high optical transmittance of a-SiN_x:H film using 162 MHz MPPP with a mixture of SiH₄/NH₃/N₂. The composition ratio between silicon and nitrogen is the key parameter to ensure the quality of a-SiN_x:H films. The optical properties of a-SiN_x:H film are closely related with the nitrogen ratio [31]. They found that the ratio between SiH₄ and NH₃ is also an important factor in a-SiN_x:H film fabrication using VHF. When the gas flow ratio of NH₃ to SiH₄ increases by 3:1, the film deposition rate increases slightly, and the number of N-H bonding rises considerably [26].

V. Conclusions

The history of VHF-PECVD for *a*-Si:H and *a*-SiN_x:H film deposition was investigated in this study. The theoretical studies on plasma excitation frequency prove that the excitation frequency can influence the EEDFs and electrical characteristics of plasma discharges. Based on these theoretical studies, VHF (30–300 MHz) was applied to film deposition processes. The two advantages of using VHF in *a*-Si:H film deposition processes — high deposition rate and good film quality — were discovered. To determine the mechanism of the high deposition rate, the properties of the VHF plasma were investigated, and the researchers discovered that VHF promotes the generation of high-energy electrons and improve the deposition rate.

In terms of the quality of a-Si:H films, the low plasma potential by the VHF plasma reduces the incident ion energy on the film surface, which leads to a low ion-bombardment defect. The gas flow rate is also an important factor for determining the film quality; the same advantages of using VHF were discovered in *a*-SiN_x:H film deposition processes. Similar to *a*-Si:H film deposition processes, the deposition rate and film quality are better than those of RF deposition processes; the high excitation frequency creates the heating mode transition that enhances high energy electrons, which leads to a large number of NH₃ dissociations and a high deposition rate. In terms of the film quality, the *a*-SiN_x:H film, which was deposited using VHF, had a high nitrogen composition rate and optical transmittance. These can be controlled by adjusting the gas flow ratio of NH₃ to SiH₄.

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