Thickness Dependent Temperature Accelerated Dielectric Breakdown Strength of On-wafer Low Dielectric Constant Polymer Films

H. K. Kim*, S. W. Lee*, F. G. Shi* and B. Zhao**

Abstract - The temperature accelerated dielectric breakdown strength of on-wafer low-k dielectric polymer films with thicknesses ranging from 94 nm to 1141 nm is investigated by using the current-voltage characteristic measurements with MIS structures. The temperature dependence of dielectric strength is demonstrated to be Arrhenious for all thicknesses. However, the activation energy is found to be strongly thickness dependent. It follows an exponential relationship rather than being a single value, i.e., the activation energy increase significantly as film thickness increases for the thickness below 500 nm, but it is almost constant for the thickness above 500 nm. This relationship suggests that the change of the activation energy corresponding to different film thickness is closely related to the temperature dependence of the electron trapping/detrapping process in polymer thin films, and is determined by both the trapping rate and the detrapping rate. Thinner films need less energy to form a conduction path compared to thicker films. Hence, it leads to smaller activation energy in thinner films, and the activation energy increases with the increase in film thickness. However, a nearly constant value of the activation energy is achieved above a certain range of film thickness, indicating that the trapping rate and detrapping rate is almost equal and eventually the activation energy approaches the value of bulk material.

Keywords: dielectric breakdown strength, thickness, temperature, low-k polymer film

1. Introduction

Low dielectric constant (low-k) materials, for replacing silicon dioxide as the interlayer insulator, are indispensable for continuous scaling of IC technology toward smaller and faster devices. In this aspect, the degradation as well as the reliability issues of low dielectric constant materials is of the main concern. Therefore, the investigation of dielectric breakdown strength is extremely important for future high performance devices. Physical properties of materials usually change with temperature, so the temperature dependence of their dielectric strength is of prime importance to analyzing their breakdown mechanism. A well understanding of the reliability issue caused by electrical stress joint with thermal stress is essential to extend device lifetime in microelectronic technology. The dielectric strength of silicon oxide has been studied extensively to explain and predict the behavior subjected to electrical and thermal stresses [1-7], however, no investigation has been reported on the temperature accelerated dielectric breakdown strength of low-k dielectric thin films with different thicknesses.

The purpose of the present work is to explore the temperature acceleration effects on the dielectric breakdown strength of on-wafer polytetrafluoroethylene (PTFE) polymer films, which has a low dielectric constant among dielectric materials [8-13]. PTFE low-k polymer films with thickness ranging from 94 nm to 1141 nm were investigated by using the current ramping voltage technique with MIS structures. It is found that the temperature dependence of dielectric breakdown strength is demonstrated to be Arrhenious. For relatively thinner films, i.e., thickness < 500 nm, the activation energy increases with the increase in film thickness. However, for relatively thicker films, i.e., thickness > 500 nm, a nearly constant value of the activation energy is observed. This observation suggests that the change of the activation energy corresponding to different film thickness is closely related to the temperature dependence of the electron trapping/detrapping process in polymer thin films, and is determined by both the trapping rate and the detrapping rate. The observed temperature dependence of the dielectric strength and the thickness dependence of activation energy is also discussed with relation to the morphology of the low-k polymer films.

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2. Experimental Details

All PTFE samples with six different thicknesses, i.e. 94, 142, 200, 528, 800, 1141 nm, were employed to investigate the temperature accelerated thickness dependence of dielectric breakdown strength. PTFE dielectric thin films were spin-coated on the silicon wafers and then baked and sintered on a computer controlled hot plate for three min with a curing temperature of 390°C [14]. Both Nanospec/AFT and ellipsometry measurements were performed to determine the thickness of polymer thin films. Total 20 points were taken to get averages. Metal electrodes of aluminum were then deposited by thermal evaporator at vacuum pressure of 1.5×10^{-6} Pa on the top surface of PTFE films.

The DC breakdown voltage was obtained by using current-voltage characteristic measurements with MIS structures in air. The DC voltage was applied to the sample until dielectric breakdown occurred and the dielectric breakdown voltage was measured. The investigation of temperature accelerated dielectric breakdown of polytetrafluoroethylene polymer films was carried out at three temperatures: 25°C, 75°C, and 150°C under electrical stress. The temperature was controlled with a programmed Athena XT-16 temperature controller with a type-K thermocouple thermometer, and temperature controller maintains deviations in the temperature within 0.1°C for accuracy of experiments. In order to attain thermal equilibrium, the sample was kept inside the chamber during the measurements.

3. Results and Discussions

Current-voltage (I-V) measurements were used to determine the dielectric breakdown strength in polytetrafluoroethylene polymer low-k thin films. A continuous increase in voltage was applied to the samples until breakdown occurred. Fig. 1 shows the variation of the dielectric breakdown strength of polytetrafluoroethylene low-k thin films as a function of the film thickness at three different temperatures, i.e., 25°C, 75°C and 150°C. The experimental data can be fitted well into the following well-known inverse power-law relationship [15-18],

$$E_{BS} \propto h^{-n} \tag{1}$$

where E_{BS} is the dielectric breakdown strength, h is the film thickness, and n is the fitting parameter. The n factor can be varied with experimental configuration, and may be related to microscopic structure, and charge transfer etc. It also has been discussed in terms of the electron affinity [15, 16, 18, 19].

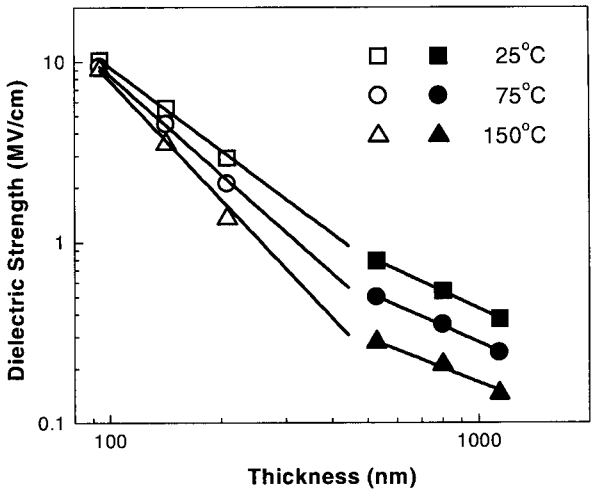

Fig. 1 Dielectric breakdown strength as a function of the polytetrafluoroethylene polymer thin film thickness with increasing temperature.

Fig. 1 evidently indicates that the dielectric breakdown strength decreases with the increase in film thickness. For an ultrathin range of film thickness, h < 100 nm, the film has the dielectric strength higher than 10 MV/cm at room temperature. The effects of the film thickness on dielectric breakdown strength has been related to charge trapping/detrapping phenomena [20, 21], materials structure, morphology, and for polymer materials, the value of n depends on the electron affinity [16]. For relatively thin film thickness, trapped charges can easily flow because trapped charges do not accumulate within insulator due to a less cumulative probability distribution of a small size. Therefore, higher electric field is needed to induce electron avalanche phenomenon and higher dielectric breakdown strength is observed in thinner film thickness ranges in the present study. Moreover, the number of traps created in thicker films compared to thinner films is more significant, and therefore the path for breakdown is easily created. In thinner thickness regions with more volume of grain boundary due to the small grain size, the lower local field across the boundary, the higher the strength of dielectric breakdown. In relatively thick films, the higher crystalline order which can be verified from Fig. 2, could contribute to a weak dielectric strength spot [22]. Further, the failure mode of thicker films can be attributed to a higher defect due to their prolonged processing stage.

All experimental data in the present study can be well described by Eq. (1), but not with a single value of n. For the thickness between 90 nm and 500 nm, n values are 1.5 at 25°C, 1.8 at 75°C, and 2.2 at 150°C respectively, which show a relatively larger value than that reported values, about 0.5 to 1.0 at room temperature [16-18]. However, for the thickness between 500 nm and 1200 nm, n values are 1.0 at 25°C, 0.9 at 75°C, and 0.8 at 150°C respectively,

which show a relatively smaller value, and is in the range of reported values. Therefore, the observed experimental data could be divided into two regions of the present study, and the distinctions between these two regions are more remarkable with the increase in temperature.

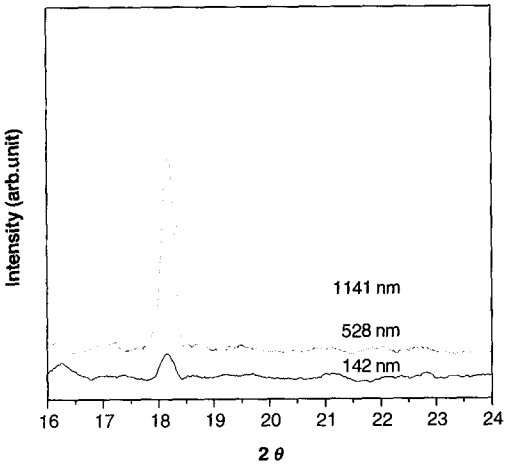

Fig. 2 Typical X-ray diffraction (XRD) patterns of the PTFE low-k thin films at room temperature.

It is generally accepted that high temperature degrades the dielectric breakdown characteristics due to the fact that thermal energy will be served as another external stress source to the charge distribution. Due to the structural change with the increase in temperatures, free electrons liberated in the polymer were accelerated, and consequently lower its dielectric strength. At relatively low temperatures, all the charged particles distribution is trapped. When temperature increases, the trapped electrons will be detrapped more easily, and less electric field is needed to initiate dielectric breakdown of the films. Hence, it is expected that E_{BS} decreases with increasing temperature, as exactly observed in the present case of polytetrafluoroethylene polymer low-k thin films shown in Fig. 3, which has been found to be still predictable by the Arrhenious law in the thickness ranges of the present study. The dielectric strength decreases with the increase in temperature at all six samples thickness ranges. This might cause harmful consequences for lifetime at operating conditions, since the increase in temperature makes samples soft, individual bond is easy to break. In this regard, electrons can interact with lattice with the increase in temperature, and consequently the lattice vibrations increase. Hence, the probability of damage increases with temperature, which can cause the dielectric breakdown. At high temperature, the charge distributions will widely spread out, hence, easy breakdown will happen compared with low temperature. Additionally, the probability of breakdown also will increase with the increase in temperature [4, 6, 23].

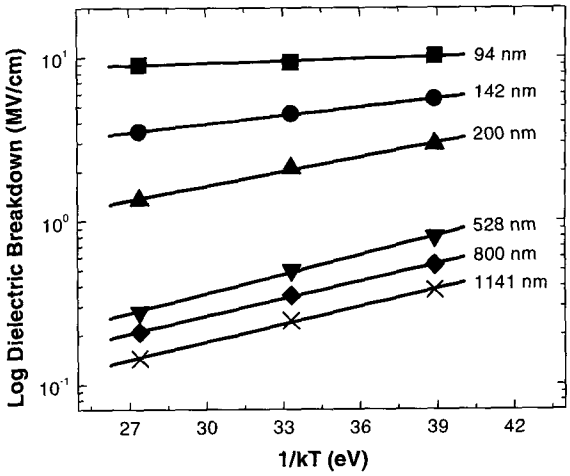

Fig. 3 Temperature acceleration effect on dielectric breakdown strength.

The activation energy E_a can be extracted from the slope of temperature dependent dielectric breakdown strength in Fig. 3. The activation energy of dielectric breakdown strength, as illustrated in Fig. 4, continuously increases with the increase in film thickness for thinner film thickness range, i.e., 0.004 eV for 90 nm, 0.017 eV for 142 nm, and 0.030 eV for 200 nm. However, the activation energy is almost constant for thicker films, i.e., 0.035 eV to 0.039 eV for 500 nm to 1200 nm, indicating a less sensitive activation energy for the thicker film thickness in the current study. From the experimental observations mentioned above, we found that the activation energy depends strongly on film thickness, and the relationship between activation energy and polymer film thickness can be described by,

$$E_a/E_0 = \exp\left[\frac{-A}{\left(h/h_0\right)^2}\right] \tag{2}$$

where E_a is the activation energy, E_0 is the bulk value of activation energy, A is a constant, h is the polymer film thickness, and h_o is regarded as the maximum thickness to retain the thickness dependency. For polymer film thicknesses above 500 nm, even though one can still observe the thickness dependent activation energy; however, the dependency is extremely weak as can be seen from Fig. 4. Hence, above the thickness of h_0, it can be considered that activation energy E_a is completely constant. The activation energy E_a will be a constant when $h \to \infty$ in Eq. (2), which indicates that E_a will approach bulk value of activation energy E_0 as h increases.

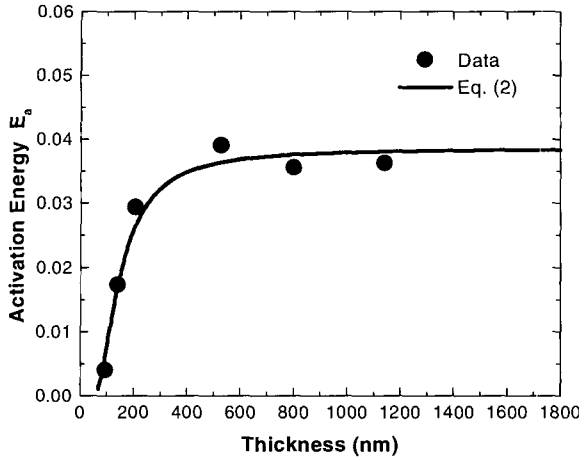

Fig. 4 Activation energy as a function of the film thickness. Solid line is obtained from Eq. (2).

In the present study, two distinct groups of thickness dependent activation energy may be due to the temperature dependence of the electron trapping/detrapping process in polymer thin films [5, 7, 24]. The electric field itself applies sufficient energy directly into samples to induce electron trap creation. The injected hot electrons break the chemical bond of samples, and liberate species, thus, a trap is produced. The breakdown occurs when the captured electrons propagates through the materials resulting in a conduction path formation. For relatively thin films, fewer traps are required to form a conduction path, and higher probability of forming a path. Therefore, the energy needed to form a conduction path is small in thinner films. It leads to smaller activation energy in thinner films, and the activation energy increases with the increase in film thickness. Therefore, from energetic point of view discussed above, thinner films should have lower dielectric strength. However, since thinner films are easy to subject to higher detrapping due to a small size and eventually a large amount of hot electron is needed to produce the dielectric breakdown. As a consequence, it was observed that thinner films have higher dielectric breakdown strength. For thicker film thickness > 500 nm, a nearly constant value of the activation energy is obtained. It means that the trapping rate and detrapping rate are almost equal above a certain film thickness from the physical point of view, and eventually the activation energy approaches the value of bulk materials. Hence, it is clear that the different behavior of the activation energy is determined by both the trapping rate and the detrapping rate. Additionally, for h > 500 nm, it may be explained that the compressive strain to the samples make a stretch of the chemical bond of samples, hence, thicker films are easy to subject to the structural imperfection due to their thickness margin provided for defects [2, 3, 7]. Also, the number of energetic interaction between electrons and lattice of films increase for thicker films due to the dispersive scattering paths. As a result, thicker films can have electrons that do not collide with lattice, and it insteadly causes impact ionization. In relatively thin films, this mechanism is inhibited due to low electron kinetic energy. Thus, for thicker film thickness, the mechanical stress due to the electric stress is dominant, and weak thickness dependent thermal stress is observed, which shows an almost constant value of the activation energy.

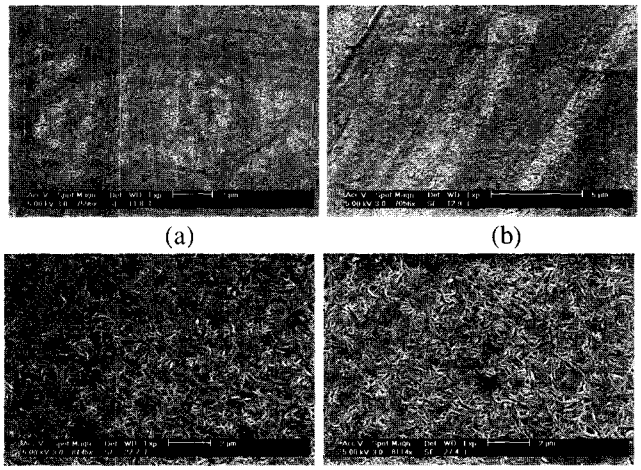

Fig. 5 Scanning electron microscopy images for the morphology of polytetrafluoroethylene polymer thin films with thicknesses of (a) 94 nm, (b) 200 nm, (c) 528 nm and (d) 800 nm.

The investigation of morphology for polytetrafluoroethylene thin films was performed with scanning electron microscopy (SEM). As shown in SEM observation of Fig. 5, the polymer film surface is composed of tightly packed wrinkles that are connected together and confined to a surface structure. For thicker films, i.e., 528 nm and 800 nm (Fig. 5(c) and (d)), the film displays a homogeneous surface in which domain sizes do not change over the entire surface area. However, for thinner films, i.e., 94 nm and 200 nm (Fig. 5(a) and (b)), a thin layer of lamellar is confined in surfaces, and the entire surface area is not homogeneous. The above observations of thickness dependence of film surface morphology show that for thinner films, their confinement to a surface structure gives a totally different morphology from thicker films. Thus, one can predict that film morphology might play an important role in determining the thickness dependence of dielectric breakdown as well as thickness dependence of activation energy, which show two distinct regions as can be seen from Fig. 1 and Fig. 4 respectively in the present study. These experimental findings might be of paramount importance from the reliability point of view for low-k dielectrics. Since the dielectric breakdown shows a strong dependence on temperature as well as thickness, and the control of microstruc-

ture can give a significant effect on their properties of low-k materials. However, further study of morphological analysis is required and is still under investigation.

4. Conclusions

The temperature acceleration of dielectric breakdown strength of polycrystalline low-k polytetrafluoroethylene thin films on silicon substrates in the thickness range of 94 nm to 1141 nm have been investigated by means of current-voltage characteristic measurements under computer-controlled heat treatments. The dielectric strength decreases with the increase in temperature for all thickness range of films. In particular, we found that the dielectric strength varies as h^{-n} (h being film thickness) and two distinct regions have been observed with two different n values; a relatively high n values, i.e., 1.5 at 25°C, 1.8 at 75°C, and 2.2 at 150°C for h < 500 nm, and a relatively low n values, i.e., 1.0 at 25°C, 0.9 at 75°C, and 0.8 at 150°C for h > 500 nm. The temperature dependence of dielectric strength is demonstrated to be Arrhenious for all thicknesses. However, the activation energy is found to be strongly thickness dependent with exponential relation rather than being a single value which shows that the activation energy increase significantly as thickness of film increases below 500 nm, but it is almost an constant for thickness above 500 nm. This relationship suggests that the different behavior of the activation energy is determined by the temperature dependence of the electron trapping/detrapping process in films. For thinner film thickness range, fewer traps are required to form a conduction path, which can lead to smaller activation energy in thinner films, and the activation increases with the increase in film thickness. For thicker film thickness (> 500 nm), a nearly constant value of the activation energy is obtained, which means that the trapping rate and detrapping rate is almost equal above a certain film thickness, and eventually the activation energy approaches the value of bulk materials. Additionally, the observed thickness dependent dielectric strength and the activation energy could be related to the morphology of polymer films.

Acknowledgements

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