Electrical conduction and breakdown properties of silicon nitride films

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The electrical conduction properties of ion-plated silicon nitride films in the form of aluminium–silicon nitride–aluminium structures have been studied in the temperature range 300 K to 470 K. The results obtained in the d.c. conduction studies have been explained on the basis of the Poole–Frenkel conduction mechanism. The a.c. conduction studies in the frequency range 500 Hz to 30 kHz indicates that the conduction may be due to the electronic hopping mechanism. The breakdown strength of the silicon nitride capacitors for various dielectric thicknesses have also been studied and the results discussed.

1. Introduction

Silicon nitride thin films are used extensively in the semiconductor industry because of their chemical stability and high resistance to diffusion of impurities [1, 2]. Also, silicon nitride has been identified as a valuable ceramic because of its superior mechanical and chemical properties at high temperature [3]. Many authors have studied the preparation of silicon nitride films and their structural and electrical properties. Most of the existing studies are, however, mainly concerned with thin films formed by sputtering [4–7], chemical vapour deposition [8–11] and r.f. glow discharge [12–15] methods. Only very little work has been done on the ion-plated silicon nitride films [16, 17]. The present paper deals with the study of the electrical conduction and dielectric breakdown properties of amorphous silicon nitride films prepared by the ion-plating technique.

2. Experimental procedure

Aluminium was deposited as the base electrode in a vacuum of 5×10^{-5} Torr onto well-cleaned glass substrates after preheating them at 523 K for 1 h. The dielectric coating was given by r.f. ion plating using an apparatus similar to that used by Murayama and Takao [18]. Prior to dielectric coating the substrates with aluminium, base electrodes were sputter cleaned for about 5 min under nitrogen pressure of 2×10^{-2} Torr and then the chamber was evacuated to a vacuum of 3×10^{-5} Torr. The substrate temperature was maintained at 523 K. A d.c. bias of 300 V was applied to the substrate holder and a r.f. power of 150 W was used. Silicon (of purity 99.999%, from Balzers) was evaporated onto the substrates using the electron-beam gun. When silicon started to evaporate, the nitrogen gas was admitted into the evaporation chamber. The pressure was maintained at 5×10^{-3} Torr and the glow discharge was initiated. A slow rate of evaporation ($0.4\ \mathrm{nm\ sec}^{-1}$) was maintained to facilitate the nitration of silicon in the nitrogen atmosphere. Finally, aluminium was evaporated over the nitride layer to complete the metal–insulator–metal (MIM) structure.

The dielectric film thickness was measured using a multiple-beam interferometer (Fizeau fringes). The structure of the films has been studied by X-ray diffractometer (Phillips, PW 1051). The d.c. conduction measurements were made using a sensitive electrometer (from the Electronic Corporation of India Ltd) maintaining a constant rate of rise of applied voltage. The a.c. conduction measurements were made using a 0.1% Universal Bridge (from Eastern Electronics, India) coupled with an audio oscillator. The breakdown studies were carried out using a stabilized d.c. power supply connected to a linear wire-wound poten-

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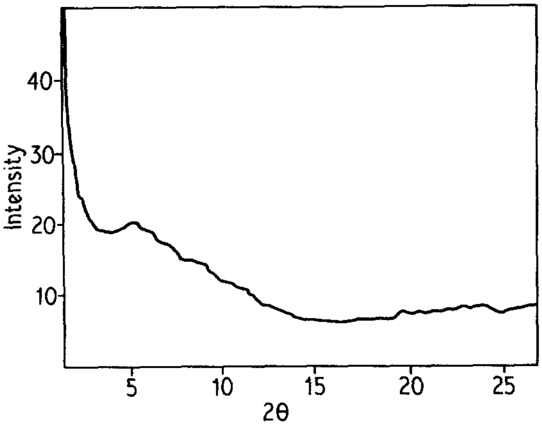

Figure 1 X-ray diffractogram for ion-plated silicon nitride films.

tiometer. A standard resistor (10 kΩ) was connected in between the source and the film. The voltage across the films was measured by a VTVM.

3. Results and discussion

3.1. Structure

The X-ray diffractogram of silicon nitride films has been given in Fig. 1. It is clear from Fig. 1 that the film is amorphous in nature.

3.2. Direct current conduction

The variation of current as a function of voltage at different temperatures for a silicon nitride film capacitor, with the dielectric thickness of 130 nm is shown in Fig. 2. From Fig. 2 it can be inferred that an ohmic behaviour is exhibited at low voltages, whereas at higher voltages the current increases exponentially. Fig. 3 shows the variation of the current with the applied field in the temperature range 300 to 456 K. The nature of the curves gives an idea of the conduction mechanism. Considering different conduction mechanisms, one can rule out tunneling, due to the thickness of the film and the high current and voltage levels. Space charge limited (SCL) conductivity is also ruled out as the SCL relationship, $I = k' V^2/d^2$, where I is the current, k is a constant, V is the applied voltage and d is the film thickness, is not followed. Finally, the linear nature of the curves indicates the possibility of any one of the two types of mechanisms: Schottky-type or Poole–Frenkel-type conduction.

The expression for the current density, J, in Schottky emission takes the form

$$J_S = AT^2 \exp\left[(e\beta_S F^{1/2} - \phi_0)/kT\right], \quad (1)$$

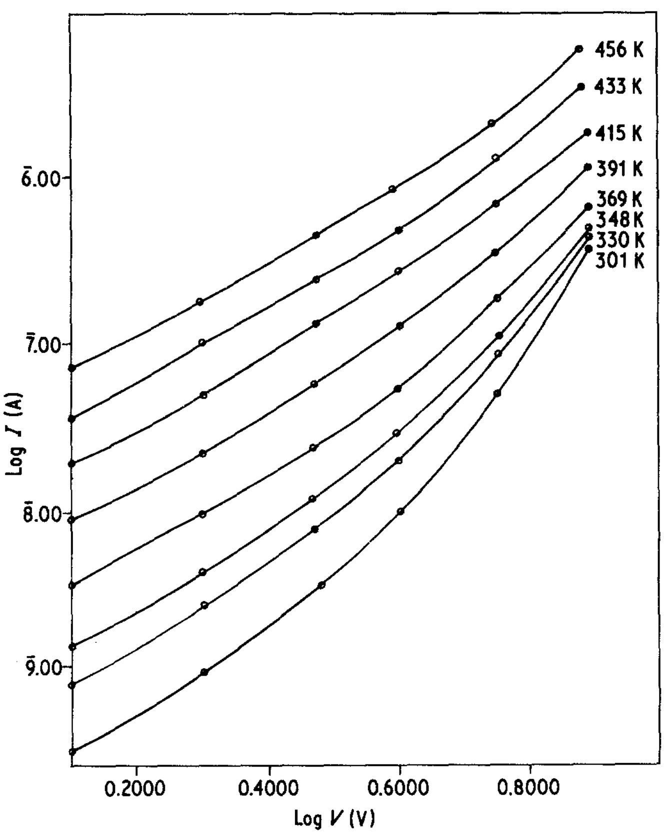

Figure 2 The variation of current, I, with voltage, V, for different temperatures of silicon nitride film having thickness 130 nm.

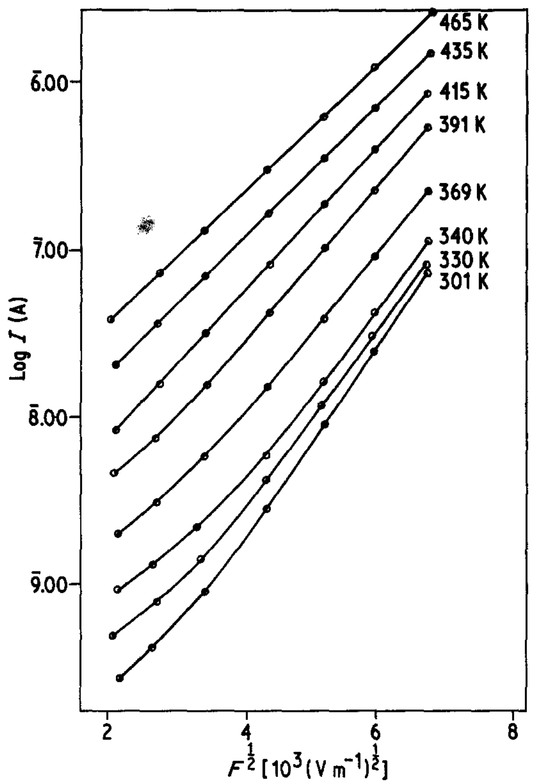

Figure 3 Plot of log T against $F^{1/2}$, where F is the applied field, for different temperatures.

where

$$\beta_S = (e/4\pi\epsilon'\epsilon_0)^{1/2}, \quad (2)$$

A is the Richardson constant, ϕ_0 is the barrier height (in eV) at the metal–insulator interface in the absence of a field, k is the Boltzmann constant, T is the temperature, e is the electronic charge, F is the electric field, ϵ' is the dielectric constant and ϵ_0 is the permittivity of free space.

In the Poole–Frenkel effect the expression for the current density takes the form

$$J_{\text{P-F}} = \sigma_0 F \exp\left[(e\beta_{\text{P-F}}F^{1/2} - \phi_0)/kT\right], \quad (3)$$

where σ_0 is the low-field conductivity and

$$\beta_{\text{P-F}} = 2(e/4\pi\epsilon'\epsilon_0)^{1/2} = 2\beta_S, \quad (4)$$

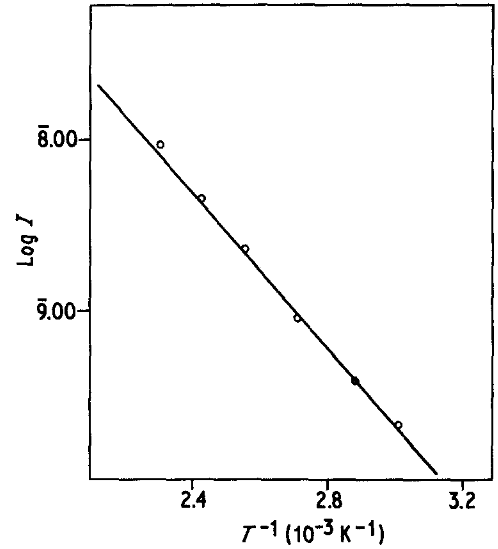

Figure 4 Log I plotted against the reciprocal of temperature, T^{-1}.

where β_S is the Schottky field lowering coefficient. For the Poole–Frenkel effect to occur (a) there must be localized centres in the material and (b) the electrons should be replenished at the cathode.

The theoretical and experimental values at different temperatures of the conduction coefficient, β, for $\epsilon' = n^2 = 4$, where n is the refractive index, are presented in Table I. From Table I it is clear that the conduction mechanism is of the Poole–Frenkel type. It is also to be noted that the nitride films contain localized levels in the forbidden energy gap, due to their amorphous nature and due to small quantities of excess silicon which may always be present in these films [19].

These localized levels may act as Poole–Frenkel centres. Many authors reported that the conduction process in silicon nitride films deposited by different methods has been dominated by the Poole–Frenkel effect [20–24].

Fig. 4 shows the relation between current and the reciprocal of temperature. The activation energy has been calculated, from the slope of the

TABLE I Theoretical and experimental values of β (for $\epsilon' = n^2 = 4$) at various temperatures

Temperature (K)	Experimental value of β [$\times 10^5$ (mV)$^{1/2}$]	Theoretical value of β [$\times 10^5$ (mV)$^{1/2}$]	
		Schottky mechanism	Poole–Frenkel mechanism
300	3.652		
330	3.604		
369	3.519	1.897	3.792
391	3.474		
415	3.464		
456	3.433		

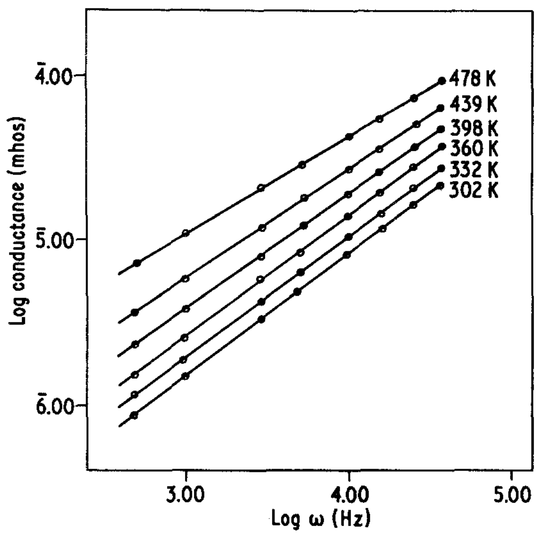

Figure 5 Plot of the a.c. conductance of silicon nitride films with thickness 130 nm against the frequency, ω, at different temperatures.

$\log I$ against T^{-1} plot, and found to be 0.413 eV at low fields.

3.3. Alternating current conduction

The dielectric constant of silicon nitride films formed by ion plating has been estimated to be 8.2 to 1 kHz. Earlier workers reported that the value of the dielectric constant varies from 5 to 9 depending on the technique used for the silicon nitride film preparation [25–28].

The variation of the a.c. conductance with frequency, ω, at different temperatures of the silicon nitride film capacitor with dielectric thickness of 130 nm is shown in Fig. 5. The conductance varies according to $\sigma'(\omega) \propto \omega^n$ with n equal to 0.8 at room temperature. Table II shows the values of n at different temperatures.

These n values are in accordance with the theory of hopping in amorphous materials [29–31]. The temperature dependence can be explained as the necessity to provide a certain amount of energy from the thermal vibration to overcome the slight

TABLE II Variation of n with temperature

Temperature (K)	n
302	0.80
332	0.75
363	0.72
398	0.70
439	0.65
478	0.55

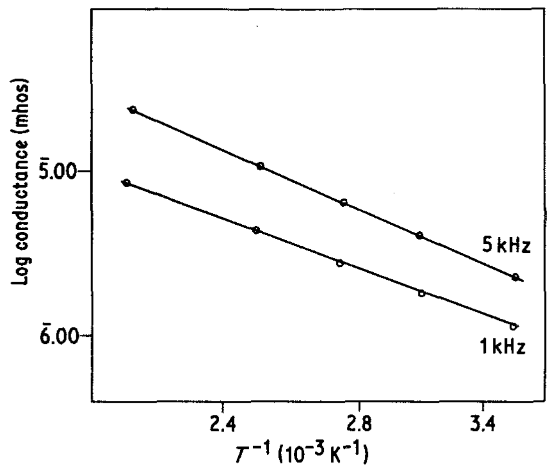

Figure 6 Plot of a.c. conductance against T^{-1}.

difference between the energy levels of the initial and final states [32]. The difference in the energy levels is due to the applied field, the stray Coulombic potential of charged centres in the lattice and to similar other causes.

Fig. 6 shows the relation between the conductance and the reciprocal of temperature, from which the activation energy has been calculated as 0.132 eV at 1 kHz and 0.168 eV at 5 kHz. These low activation energy values suggest that the charge carriers involved in the hopping conduction are electrons. The a.c. conductivity of dielectric films is over two orders of magnitude higher than the d.c. conductivity value. This suggests that the a.c. conduction mechanisms are different from those of d.c. conduction or that the charge transport is more efficient under the a.c. conduction [33].

3.4. Breakdown studies

Measurement of the d.c. breakdown field strength, F_b, of ion-plated silicon nitride film capacitors has been carried out in the dielectric films of thickness in the range 30 to 200 nm. In Fig. 7 the log of the breakdown field is plotted against the log of the film thickness, d. The dielectric strength has been found to be a power-dependent function of thickness varying as $d^{-\alpha}$, with $\alpha = 0.51$. This is in accordance with the theory of Forlani and Minnaja of electronic breakdown which predicts a relation $F_b \propto d^{1/2}$ when the applied field is large and the dielectric has a high energy gap [34]. Silicon nitride has a large energy gap of 4 eV [4]. The breakdown strength of silicon nitride films prepared by the ion plating method is in accordance with the earlier reports for silicon nitride films prepared by other methods [11, 35, 36].

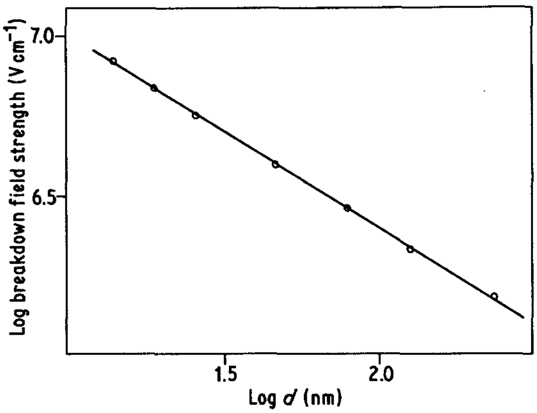

Figure 7 Variation of breakdown field strength with the thickness of silicon nitride film.

4. Conclusion

The d.c. and a.c. conduction properties of ion-plated silicon nitride films in the form of the aluminium–silicon nitride–aluminium capacitor structure has been studied in the temperature range 300 to 470 K. It has been found that in the d.c. conduction studies the Poole–Frenkel type is the dominating conduction mechanism. The dispersion of conductance with frequency under a.c. fields leads to the fact that the electronic hopping mechanism is operating in the frequency range studied. The breakdown strength of the silicon nitride thin film capacitors has been found to be a power-dependent function of thickness, as already predicted by Forlani and Minnaja. The dielectric strength of these films has been found to be approximately 5×10^6 V cm^{-1}.

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