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Electrical conduction in polyimide films

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Abstract : Current transport mechanisms in thin polyimide films have been studied over the temperature range of 300 K–425 K. It is found that at low fields the films exhibit an ohmic behavior which is consistent with hopping of electrons between localized levels present in the band gap in amorphous materials. High field region is dominated by a Poole-Frenkel type mechanism. The activation energy of the Poole-Frenkel centers have been measured to be 1 1 eV. A band model is used to explain the experimental results

Keywords : Polymer films, conduction mechanisms, Poole-Frenkel effect.

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Polymers have been studied extensively with a view to access their suitability for application in electronic devices [1]. Both, the speed and reliability of these devices are the prime considerations. The speed of signal propagation in these devices is inversely proportional to the square root of the dielectric constant [2]. Thus the materials with lower dielectric constant and dissipation factor will allow a higher density of metal connections. Higher reliability and stability of devices require minimal residual thermal stress and high adhesive strength.

Polyimide has been found to exhibit not only good adhesive properties but has also been found attractive in electronic and microelectronic device applications particularly because of its continuous service temperature up to 350°C with excellent electrical and mechanical properties [3]. Consequently, polyimide films have been used as a dielectric, an insulator and in multichip packaging [4].

Performance of the electronic devices is limited by the leakage of current through the insulating polyimide films. Current voltage characteristics as a function of temperature have been studied for commercially available highly insulating films of electrical grade polyimide with the hope that an understanding of the fundamental nature of the current transport mechanisms operative in these films will help in the better design of the electronic devices.

Commercially available electrical grade polyimide films were used for the study. These films were available in standard thicknesses of 12.5 and 25 microns. They showed a deep amber color and were reported to be stable up to 400°C.

To study the current voltage characteristics the films were sandwiched between metal electrodes so that currents at high fields could be induced by manageable voltages. Metal electrodes were evaporated on either side in a vacuum better than 10^{-5} torr. Two sandwich configurations namely, aluminum/polyimide/aluminum and copper/polyimide/aluminum were studied. The total active area of polyimide was 2.00 sq cm. Electrical connections were made using conducting silver paste.

IV-characteristics were obtained by applying the voltage across a series combination of the specimen and a standard resistor placed inside a shielded box. Current passing through the specimen produced a voltage across the standard resistor which was measured by a Keithley 610°C electrometer. Currents down to 10^{-14} amps could be measured. An extremely stable DC supply was made by connecting several battery packs to provide 3000 volts. A shielded heater was also built inside the specimen box. A Skil-79 temperature controller was used to hold the sample at any temperature between *ca* 300 K (room temperature) and 450 K. A Chromel-Alumel thermocouple was used as the temperature sensor.

Current voltage behavior was measured in 12.5 and 25 microns thick films. Data at 300 K for both the films are shown in Figure 1. The currents are identical in both the cases provided the fields across the polyimide films are taken into account. This indicates that the conduction mechanism is bulk dominated. At low fields an ohmic region is obtained. The high field data when plotted on a log I *vs* $V^{1/2}$ scale, as shown in Figure 2, exhibits a linear relationship. Such a behavior has usually been associated with a barrier lowering type mechanism which can either be an image force induced electrode effect [5] or the thermal ionization of carriers of a donor type center in the bulk of the material [6].

Current due to either direction of the applied field was virtually similar indicating again a bulk controlled process. This was true even for asymmetric electrode configuration. Several sandwich structures of Cu/polyimide/Al were studied in addition to Al/polyimide/Al configurations. They all exhibited similar behavior.

Figure 2 also shows a variation of current over a temperature range of 300 K–425 K. It is obvious that the onset of the linear region moves to higher voltages with increasing temperature. Such a behavior is consistent with the Poole-Frenkel type phenomenon where thermal excitation of the carrier takes place over a field lowered barrier. The lowering of the barrier is given by $\Delta\phi = \beta E^{1/2}$ where β is the barrier lowering coefficient and E is the applied field. The effect of barrier lowering is reduced due to increased thermal energy of the trapped electrons.

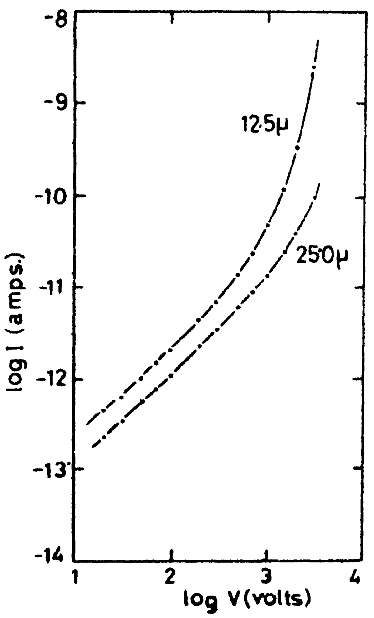

Figure 1. Current-voltage characteristics for 12.5 and 25 μm thick polyimide samples.

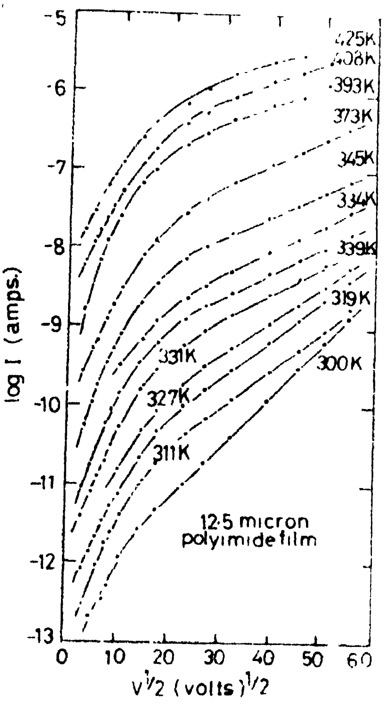

Figure 2. ln I–$V^{1/2}$ characteristics for 12.5 μm polyimide film sandwiched between aluminum electrodes

Figure 3 shows the Arrhenious plots. It is found that the activation energy varies from 1.1 eV at 10 volts to 0.8 eV at 3 kV of applied bias *i.e.* a total change of 0.3 eV over the voltage range. This experimentally observed reduction of the activation energy gives a value of β at 2.3×10^{-5} $m^{1/2}$ $V^{1/2}$. This is less than the theoretical value of 3.8×10^{-5} $m^{1/2}$ $V^{1/2}$ for a dielectric constant of 2.0 for polyimide. However, it has been pointed out that the true criterion for the existence of a Poole-Frenkel type process is not so much the value of β but whether the process is bulk controlled [6] for which ample experimental evidences exist in this case.

Polyimide films studied here have an amorphous structure. Consequently, energy bands are expected to display a distribution of energy levels which become increasingly localized with their energetic distance from the band edges [7]. On the basis of experimental evidence current transport in polyimide films at low fields can be considered a consequence of electrons hopping down the potential gradient at the Fermi level giving the observed ohmic behavior.

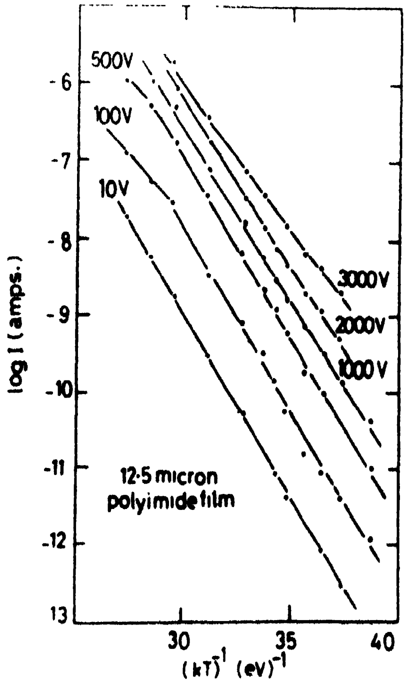

Figure 3. Activation energy plot for a 12.5 μm polyimide film over a wide range of bias voltages.

On the other hand at increased fields the deep donor like centers are expected to play a role. In a classic Poole-Frenkel behavior the carriers are thermally excited over a field lowered barrier giving the ln I–$V^{1/2}$ relationship. The activation energy of these centers as determined experimentally is around 1.1 eV. This also explains why the onset of the Poole-Frenkel region shifts to higher voltages (fields) with increasing temperatures.

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