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Electronic properties of $Cu/SiO_2/Cu$ structures at different temperatures

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Abstract

In this experimental work, some electronic properties of vacuum evaporated $Cu/SiO_2/Cu$ structures such as circuiting I_c and emission I_e currents versus the applied voltage, electron attenuation lengths in both copper and SiO_2 layers and the role of the latter layers have been investigated. Experimental results show that these devices undergo an electroforming process leading to resistivity decrease of several orders of magnitude along with a negative resistance region in their current–voltage characteristics. By decreasing the temperature, both I_c and I_e are decreased and at low temperatures the negative resistance region disappears completely. Electron attenuation lengths are measured between 6 and 14 V for copper and SiO_2 layers and their significance are discussed on the base of electron-impurity and electron-defect scatterings. The conduction mechanism is also discussed on the base of a filamentary model.

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1. Introduction

Thin layers of insulators sandwiched between two metal electrodes exhibit a number of interesting properties. When a bias voltage is applied across an unformed sample an electroforming process takes place in the dielectric layer and its resistance is decreased. After electroforming, devices in which the dielectric is an oxide or oxide complex generally show a voltage-controlled negative resistance, electroluminescence, electron emission into a vacuum and a possible memory effect.

The mechanism of electron transport through thin insulating films sandwiched between metal electrodes has been the subject of a number of investigations and a number of theories to explain the *I*–*V* and related characteristics has been given. One of the models which successfully explain the observed phenomena was put forward by Dearnaley et al. [1]. Their model explains the conduction of field induced metallic filaments in the dielectric matrix sandwiched between the two electrodes thereby providing low-resistance paths for the current, and electron emission takes place from the ends of these filaments at the top positive electrode [1,2]. To study the energy loss mechanism in these samples, the transfer ratio is measured as a function of thickness of top or the insulator layers which in turn leads to direct measurements of the hot electron attenuation lengths in these layers. The transfer ratio is defined as the ratio of electron emission current I_e to the circulating current I_c for a given voltage applied across the sandwich. Results of such experiments indicated a strong attenuation of electrons in the top metal electrode and also provided evidence of inelastic interactions of the injected electrons in the top layer [3–5].

In the present paper, measurements are reported on $Cu/SiO_2/Cu$ structures in which the usual phenomena of

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electroforming, negative resistance and electron emission into a vacuum are observed. Reasonably good electron emission properties are found and hot electron attenuation lengths are determined for the Cu and SiO_2 layers. The study of vitreous Silica, the amorphous silicon dioxide which was used in this study, is currently an attractive research field in solid state physics and material science [6,7]. The physical properties of high transparency in a wide spectral region and low conductivity, in combination with favorable mechanical characteristics and low manufacturing costs, have led to the wide spread utilization of silica-based materials in many technological applications like manufacturing of optical fibers, lenses and optoelectronic devices. These exceptional features depend critically on the maintenance of defect free band gap [8]. For this reason the understanding of the nature of defects in SiO_2 layers plays a fundamental role in both the technology and basic research. As we are mainly concerned with the electronic properties of $Cu/SiO_2/Cu$ structure such as I_c-V and I_e-V characteristics, temperature dependence of conductivity and electron attenuation length in both copper and SiO_2 layers, the structural properties of the SiO_2 layers will not be given in this paper. Nevertheless, the main role played by the vitreous matrix from the stand point of defect in determining the electron attenuation lengths in the SiO_2 layers will be given.

2. Experimental techniques

The layers used in this experimental work were prepared by vacuum evaporation of Cu and SiO_2 from different sources in a Balzers 760 coating unit by electron bombardment. To control the deposition rate and thickness of samples, two separate quartz crystal monitors were used. All samples used in this study were prepared by successive evaporation of the various layers without breaking the vacuum. For one evaporation procedure, eight specimens were prepared on each Corning glass substrate having different metallic or dielectric thicknesses.

2.1. Measurements

All measurements were carried out in a vacuum system capable of maintaining the samples at a pressure of about 5×10^{-6} Torr. The current–voltage characteristics were measured by traditional methods. To measure the temperature dependence of I–V characteristics and also the electron emission from $Cu/SiO_2/Cu$ specimens, a small heater was used along with a metal cryostat which could be filled continuously with liquid nitrogen. A stabilized power supply unit was used to feed the heater and by judicious use of cryostat and heater the required temperatures could be obtained. Device temperatures were recorded from a copper constantan thermocouple connected to the surface of the substrate. Electrons emitted into vacuum were collected at a copper anode placed at a distance of 1.0 cm from the samples. Anode was kept at a potential of 100 V with respect to earth. A keithley 610 C electrometer which was capable of measuring currents of the order of 10^{-15} A was used for measurement of the emission currents.

2.2. Electron attenuation length measurements

Measurements of the relative numbers of electrons emitted through the thin top layer as a function of layer thickness yield directly values of the hot electron attenuation length λ_{Cu}. To determine λ_{SiO_2} experimentally, samples with constant top electrode thickness but with insulator layers of different thicknesses were prepared.

3. Results

3.1. Electrical characteristics

The conductivity of the samples increases by several orders of magnitude when they are electroformed at room temperature in vacuum. As the applied voltage across the sample is gradually increased, a critical voltage is reached at which a sharp increase in current through the SiO_2 layer occurs. On raising the voltage to successively higher values, the current–voltage characteristics continue to show a negative resistance region for both increasing and decreasing voltages. The electroforming process consists of cycling the voltage applied across the sandwich between 0 and 12 V with top electrode positively biased. The voltage required for forming increases with the SiO_2 layer thickness and it was found possible to form sandwich electrically in which the SiO_2 layer thickness was 1.5 μm. The forming voltage increased with decreasing temperature. The onset of electron emission into a vacuum occurred for the same applied voltage as that at which the voltage-controlled negative resistance (VCNR) occurred. Typical curves illustrating the circulating and emission currents in a $Cu/SiO_2/Cu$ sandwich at room temperature are shown in Figs. 1 and 2.

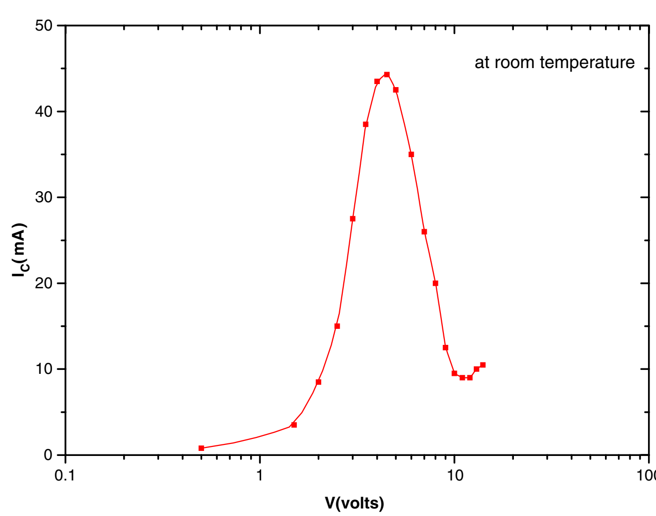

Fig. 1. Variations of circulating current versus the applied voltage for a $Cu/SiO_2/Cu$ sample.