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Effect of laser irradiation on C–V characteristics of electrodeposited Ag/Tl-2223/CdSe hetero-nanostructures

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Abstract. One of the innovative technological directions for the high-temperature superconductors has been persued by fabricating the heteroepitaxial multilayer structures such as superconductor–semiconductor heterostructures. In the present investigation, metal/superconductor/semiconductor (Ag/Tl-2223/CdSe) hetero-nanostructures have successfully been fabricated using dc electrodeposition technique and were characterized by X-ray diffraction (XRD), full-width at half-maximum (FWHM) and scanning electron microscopy (SEM) studies. The measurement of junction capacitance as a function of biasing voltage was used for the estimation of junction built-in-potential (V_D) and to study the charge distribution in a heterojunction. The Mott–Schottky plots were measured for each junction in dark and under the photo-irradiation. The effect of laser irradiation on C–V characteristics of hetero-nanostructure has been studied.

Keywords. Electrodeposition; Tl-based cuprate; semiconductor; nanostructure; capacitance measurement; heterostructures; electrical properties.

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1. Introduction

The development of energy devices with high T_c superconductors (HTSC) is energizing worldwide efforts to expand the established superconductivity industries. Research in thin film and multilayer HTSC's is driven by potential electrical and electronic device applications. Device-quality superconducting films must be grown at industrially viable growth rates on large areas and flat surfaces. For many applications, these superconductors must be integrated in multilayers with normal metals, insulators and/or superconductors. Some progress has been made in the growth of high-temperature superconducting thin films on Si [1] and GaAs [2,3]. A major problem in using Si and GaAs as a substrate for the HTSC films is the substrate–film interdiffusion and the formation of microcracks in the film due to relative difference in thermal coefficient of expansion between the semiconductor and HTSC [4]. The heterostructure between Bi-2212 (BSCCO) and GaAs showed great enhancement in superconducting critical transition temperature from 71 K to 83 K by depositing GaAs on the top of BSCCO [4]. Pawar *et al* have fabricated a junction between BSCCO and CdSe and reported that T_c value could possibly be raised as high as 250 K [5,6].

The superconducting transition temperature can be increased by photodoping. The photodoping could lead not only to an increase in conductivity, but could also possibly enhance T_c [7]. In oxygen deficient materials, it has been shown that illumination of high T_c superconductors with visible [8–10] or ultraviolet light [11] induces persistent photoconductivity [8] and photoinduced superconductivity [9,10]. The sharp increase in the conductivity of $YBa_2Cu_3O_x$ (YBCO) samples has been observed when photon flux from the nitrogen lasers exceeding 10^{15} photon/cm^2 was applied [12–14]. In the light of this work, we have planned to fabricate the metal–superconductor–semiconductor heterostructure and to study the normal state changes in the conductivity across the junctions by laser irradiation. For superconductor–semiconductor heterostructure studies, we have selected Tl-2223 system with the highest T_c and J_c as the best alternative candidate to YBCO and BSCCO. Further, the semiconductor CdSe is used in heterostructure fabrication as it has good photosensitive and nano-crystalline property [15].

In the present investigation, the heterostructure of superconducting Tl-2223 and semiconducting CdSe was fabricated on silver substrate by using electrodeposition technique. The X-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques were used to characterize the heterostructure. The C–V characteristics before and after laser irradiation were measured to estimate the value of built-in junction potential (V_D). The effect of laser irradiation on the properties of these heterostructures has been studied.

2. Experimental

The heterostructure between metal, superconductor and semiconductor was fabricated by using electrodeposition technique which has many advantages over other techniques including high deposition rate and the ability to fabricate material in any shape and size. The Tl–Ba–Ca–Cu alloy was co-deposited on Ag foil followed by electrochemical oxidation with $T_c = 114$ K [20]. Then semiconductor CdSe was deposited on Tl–Ba–Ca–CuO layer to form the heterostructure between them [21].

Microstructure of as-deposited CdSe and Tl–Ba–Ca–CuO superconducting film and heterostructure was observed using a close circuit television (CCTV) attachment to Metzer optical microscope (450×) in reflection mode and by using SEM CAMECA Model SU 30.

X-ray diffraction data was obtained on microcomputer-controlled Philips PW-3710 diffractometer using CuK_α radiation. The FWHM was used to calculate the particle size by applying Scherrer's formula. Thermoelectric power (TEP) measurements were carried out on a specially designed kit for thin films. The C–V characteristics is a key technique to study the built-in junction potential (V_D) and type of junction formed between Ag, Tl–Ba–Ca–CuO and CdSe. Square type contacts with equal area were made by air-drying silver paint. The junction capacitance was measured using FORBES model LCR-Q meter at 10 kHz frequency and by applying external bias voltage. He–Ne laser with power 2mW, $\lambda = 632.8$ nm and photon energy = 1.95 eV was used to irradiate the sample. The C–V characteristics were studied in dark and under photoexcitation at room temperature.

3. Results and discussion

3.1 *XRD, microstructure and TEP studies of heterostructure*

Figure 1 shows the XRD pattern of Ag/Tl–Ba–Ca–CuO/CdSe heterostructure. The presence of major peaks (0014), (118), (0015), (0018), (1114), and (1023) confirms the tetragonal Tl-2223 phase and the presence of peak (100), (200), (110), (103), (201) and (203) confirms the hexagonal semiconductor CdSe. The particle sizes of CdSe and Tl-2223 were calculated from FWHM method and were found to be 25 nm and 33 nm, respectively. The XRD pattern shows the presence of both superconducting Tl-2223 and semiconducting CdSe. The calculated *c* parameter of Tl-2223 is 35.76 Å and CdSe is 7.1 Å. These are in good agreement with the values reported earlier and confirm the hetero-nanostructure.

The microstructures of CdSe, Tl–Ba–Ca–CuO and Ag/Tl–Ba–Ca–CuO/CdSe were observed with Metzer optical microscope and it was found that films were uniform and well-covered. The SEM images of CdSe and Ag/Tl–Ba–Ca–CuO/CdSe heterostructure are shown in figures 2a and 2b. The films were found to be smooth, pore free, dense and adherent to the substrate. The TEP measurements of Tl–Ba–Ca–CuO and CdSe were carried out to study the type of carrier concentration. The TEP measurement for Tl–Ba–Ca–CuO show p-type charge carrier (holes) and CdSe show n-type charge carriers (electrons).

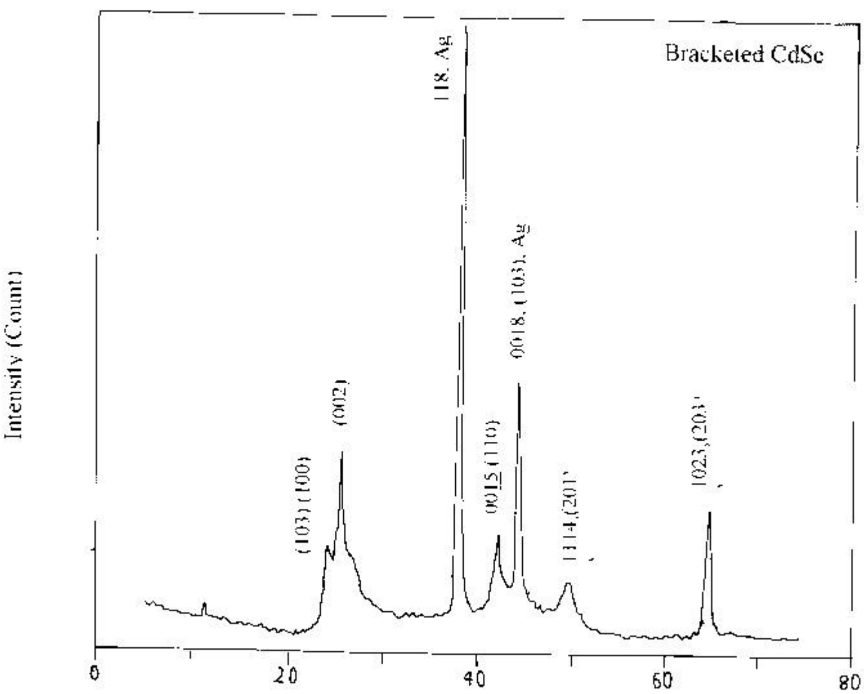

Figure 1. X-ray diffraction pattern of Ag/Tl-2223/CdSe heterostructure.

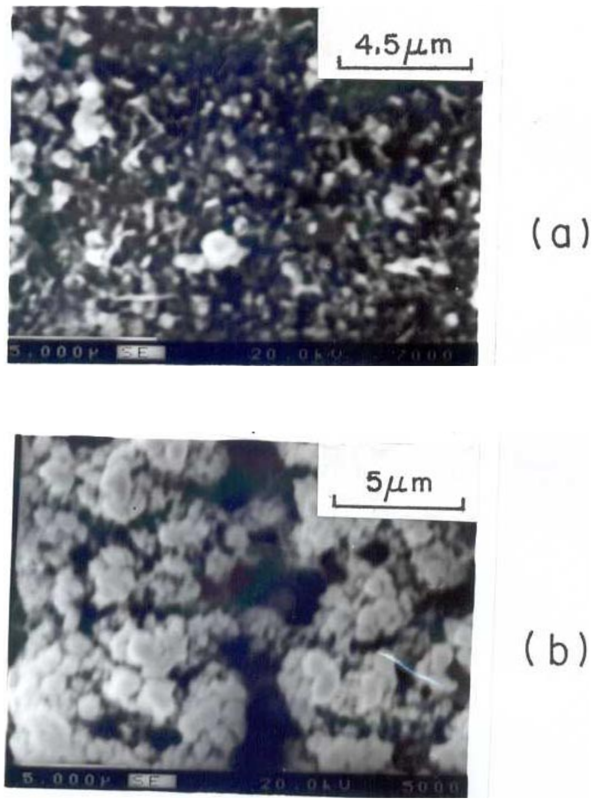

Figure 2. SEM images of (**a**) CdSe and (**b**) Ag/Tl-2223/CdSe films.

3.2 *Measurement of photoinduced changes in C–V characteristics of heterojunctions*

It is very essential to know the type of conductivity of individual deposit and effective band diagram of each heterostructure in order to apply the voltage in its forward and reverse biased condition. The CdSe has band-gap energy of 1.72 eV. But high-temperature superconductors have pseudo-band gap. Hence, it is difficult to draw the neat energy band diagram for metal–superconductor–semiconductor heterojunctions. In principle, the energy band profile of any heterojunction, in the absence of interface states (mainly lattice matching and depletion), depends upon electron affinities, energy band gaps and work functions of the two semiconductors forming the heterojunction. Hence, for metal–superconductor junction in particular, it is difficult to determine the forward and reverse biasing, as formation of depletion region (positive space charge) or accumulation region (negative space charge) depends on work function.

Hence, in the present investigation the metal–superconductor junction capacitance has been measured by applying forward and reverse biased potentials. And for superconductor–semiconductor and metal–superconductor–semiconductor heterojunction, junction capacitance was measured in reverse biased state. Heterojunctions were illuminated by red

He–Ne laser (with $\lambda = 632.8$ nm, power = 2 mW and photon energy = 1.95 eV) and capacitance was measured as a function of photon dose.

3.2.1 *Ag/Tl–Ba–Ca–CuO heterojunction*: Figure 3 shows the plots of capacitance vs. bias potential. It is observed that the capacitance decreases with increase in the forward or reverse bias voltage, applied across the junction. The phenomenon of decrease in capacitance might be due to the formation of large depletion region essentially in superconducting region. Also it might be due to the fact that there is lattice mismatch between Ag and $Tl_2Ba_2Ca_2Cu_3O_{10}$ and the formation of insulating phase across the interface.

When the junction is illuminated with laser it is observed that the value of capacitance has increased and continues to increase with increase in the photon dose and gets saturated after 3 h. When the superconductor in contact with the metal is irradiated with laser of photon energy 1.95 eV there is a production of electron–hole pairs across the junction, which drift in the junction, and hence, increase the capacitance. Figure 4 shows the Mott–Schottky plot for $Ag/Tl_2Ba_2Ca_2Cu_3O_{10}$ junction. It is observed that the plot of $1/C^2$ vs. V is a straight line and the slope of the plot decreases with the irradiation of the junction using laser. The extrapolated plots meet voltage axis at -0.1 V to -0.3 V which gives the built-in junction potential to be 0.1 to 0.3 eV. The decrease in slope indicates that there is increase in carrier concentration across the junction.

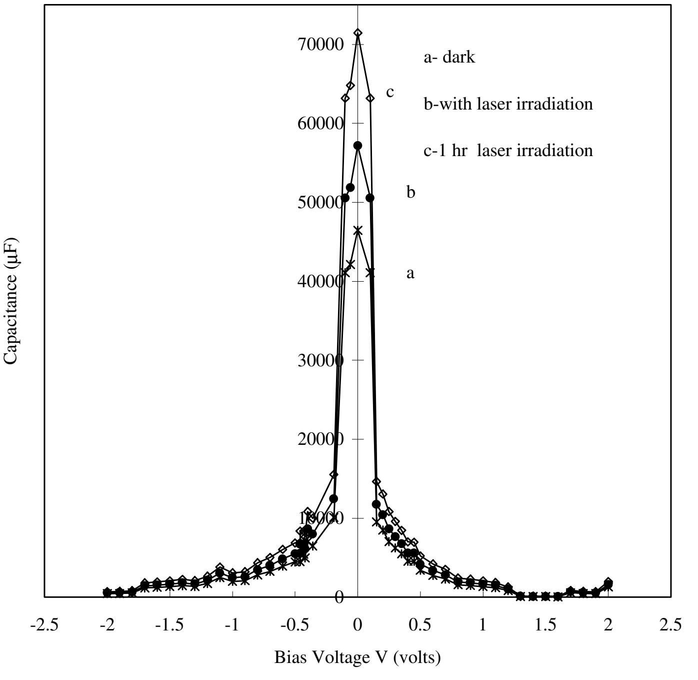

Figure 3. Plot of C–V curves for Ag/Tl-2223 junction in dark and under laser irradiation.

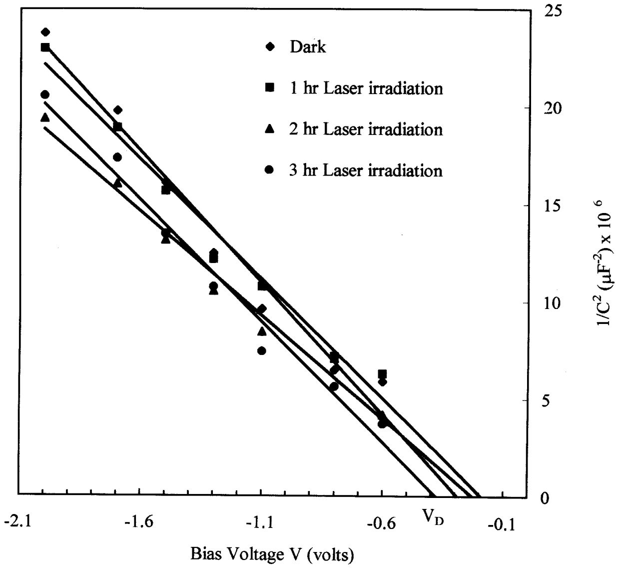

Figure 4. Mott–Schottky plots for Ag/Tl-2223 junction in dark and under laser irradiation.

3.2.2 *Tl–Ba–Ca–CuO/CdSe heterojunction*: The *C–V* characteristics of $Tl_2Ba_2Ca_2Cu_3O_{10}$/CdSe heterojunction was measured by applying reverse biased potential, i.e., negative terminal of potential is applied to superconductor and positive terminal is applied to CdSe film. Figure 5 shows Mott–Schottky plot for this heterojunction in dark and with laser irradiation. The nature of the plot clearly shows abrupt p–n junction characteristics. The plot in dark is a straight line. It continues to decrease as the applied photon dose increases and attains the saturation state after 3 h. When heterojunction was just irradiated with light the slope of the plot was found to be decreased. This is attributed to the increase in capacitance due to increase in charge carriers across the junction where electrons are drifted in n-region and holes are drifted in p-region. The extrapolated plots intersect on bias voltage axis at 0.75 V giving the value of built-in junction potential to be 0.75 eV. The crossover of the extrapolated plot on voltage axis shows the formation of abrupt p–n, (p)Tl-2223/(n)CdSe, junction. But the increase is equal in magnitude for both types of charges; hence, essentially built-in junction potential has not changed. This also indicates that there are no structural changes or diffusion across the junction due to laser irradiation.

3.2.3 *Ag/Tl–Ba–Ca–CuO/CdSe heterojunction*: Figure 6 shows the Mott–Schottky plot for Ag/Tl-2223 /CdSe heterojunction in dark and with laser irradiation. The nature of the plot shows the formation of abrupt heterojunction. The plot in dark is a straight line. The slope of the plot is found to be decreased with irradiation of the heterojunction indicating increase in junction capacitance. The extrapolated plots meet at about the same potential −0.78 V and gives the built-in junction potential to be 0.78 eV. The magnitude of the

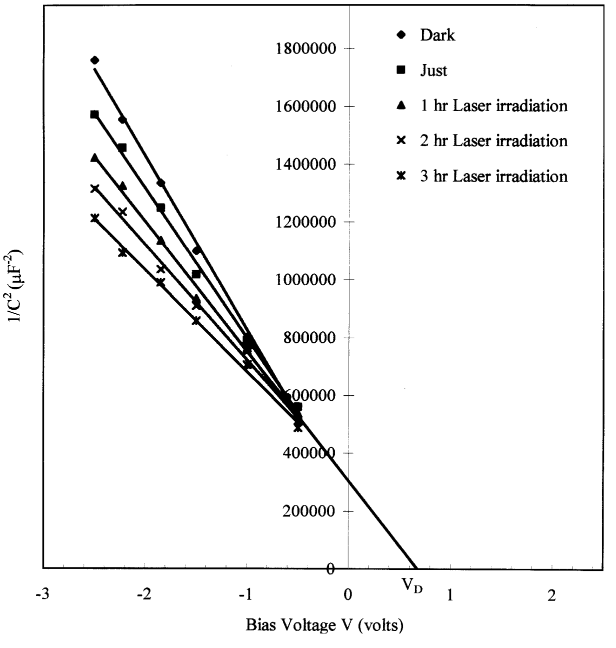

Figure 5. Mott–Schottky plots for Tl-2223/CdSe junction in dark and under laser irradiation.

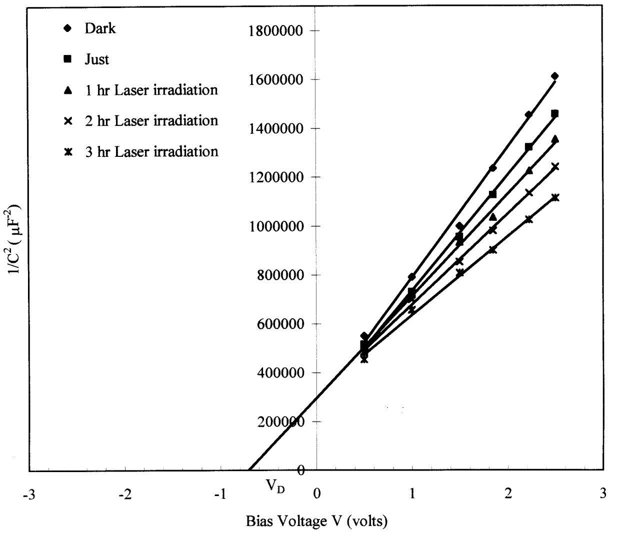

Figure 6. Mott–Schottky plots for Ag/Tl-2223/CdSe junction in dark and under laser irradiation.

change in slope of this junction is greater than the previous case, clearly indicating an increase in charge carriers in sandwiched superconductor junction due to laser irradiation. The low temperature studies of these heterojunctions are in progress.

4. Conclusion

Electrodeposition technique is proved to be a novel technique for the fabrication of Ag/Tl-2223/CdSe heterostructures. The increase in capacitance with increase in photon dose indicates the increase in carrier concentration across the junction during the laser irradiation.

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