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Studies on photoinduced effects in pulse-electrodeposited Ag/Hg-1212/CdSe hetero-nanostructures

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Abstract. Metal/superconductor/semiconductor (Ag/Hg-1212/CdSe) hetero-nanostructures have been fabricated using pulse-electrodeposition technique and are characterized by X-ray diffraction (XRD), full-width at half-maximum (FWHM) and scanning electron microscopy (SEM) studies. The junction capacitance of Ag/Hg-1212, Hg-1212/CdSe and Ag/Hg-1212/CdSe heterojunctions is measured in dark and under laser irradiation at room temperature. The nature of the junction formed and built-in-junction potentials were determined. The increase in carrier concentration across the junction due to photo-irradiation has been observed.

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

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1. Introduction

The micro-cryoelectronics and hybrid devices are based on the use of superconducting thin films integrated with multilayers of metals, insulators, semiconductors and/or other superconductors. Superconductor–semiconductor (super–semi) hybrid devices include non-hysteretic Josephson junctions and several different types of three-terminal devices, in which the coupling between high-temperature superconductor (HTSC) layer is provided by a semiconducting layer. Some progress has been made in the growth of multilayers with HTSC thin films on Si [1] and GaAs [2]. The major problem in using Si and GaAs as a substrate for HTSC film is the substrate–film interdiffusion and the formation of microcracks in the film due to relative difference in thermal coefficient of expansion between the semiconducting and HTSC films. The heterostructure between BSCCO and GaAs formed by depositing GaAs onto BSCCO by molecular beam epitaxy technique showed great enhancement in T_c from 71 K to 83 K [3]. Rao *et al* [4] have grown InAs on TlBaCaCuO superconducting film. Pawar *et al* [5,6] have observed anomalous behavior in I–V characteristics of Ag/BSCCO/CdSe heterostructures at 250 K, suggesting a possibility of increasing T_c as high as 250 K.

The recent experimental evidence [7] showed that photodoping could improve the superconducting transition temperature and the growth of the superconducting phase. In oxygen deficient materials it has been shown that illumination with visible light [8] or ultra-violet light [9] induces persistent photoconductivity [10] and photoinduced superconductivity [11]. A sharp increase in the conductivity of $YBa_2Cu_3O_x$ samples in semiconducting state, has been observed when photon flux from the nitrogen laser exceeding 10^{15} photons/cm^2 was applied [12].

The development of such heterostructures requires suitable growth techniques, which will retain key electronic properties of both the materials. Besides other thin film deposition techniques, the pulse-electrodeposition technique provides a highly reactive mixture on atomic scale which markedly reduces the time and temperature and it gives highly conducting nonporous and fine grained deposits [13]. In the present investigation, Ag/Hg-1212/CdSe heterojunctions are fabricated first time by employing the pulse-electrodeposition technique. $Hg_1Ba_2Ca_1Cu_2O_{6+\delta}$ (Hg-1212) system is used because of its high T_c value. The semiconducting CdSe is chosen considering its lattice and thermal agreement and good photosensitive and nanocrystalline properties. Besides T_c and J_c values, the quality of superconducting heterojunction is determined by the interface states. Interface states can be studied by I–V and C–V measurements. This paper reports the effects of photoexcitation on C–V characteristics of Ag/Hg-1212/CdSe hetero-nanojunctions.

2. Experimental

The Hg-1212 superconducting thin films deposited by pulse-electrodeposition show superconductivity at 104.7 K [14]. The fabrication of Ag/Hg-1212/CdSe heterojunctions by pulse-electrodeposition technique and photoinduced effects on its I–V characteristics are reported elsewhere [15]. XRD data of heterostructure was obtained with Philips PW 3710 diffractometer using CuK_α radiation. The particle size was calculated using full-width at half-maxima (FWHM) and by applying Scherrer's formula. The microstructural studies were carried out with CAMECA model SU 30 SEM. Thermo-electric power (TEP) measurements were carried out on specially designed kit for thin films. Square type contacts with equal area were made onto deposits forming the heterojunction 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, to study the C–V characteristics of these heterojunctions. The red He–Ne laser with $\lambda = 632.8$ nm, power = 2 mW and photon energy = 2.01 eV was used to irradiate the hetero-nanostructures.

3. Results and discussion

3.1 *XRD and SEM characterization*

Figure 1 shows X-ray diffraction pattern of Ag/Hg-1212/CdSe heterostructure. It is observed that the pattern contains planes of tetragonal Hg-1212 and hexagonal CdSe structures. The reflection peaks from silver substrate are also marked. The c-lattice parameter was calculated for both the systems present in heterostructure and are 12.66 Å for Hg-1212

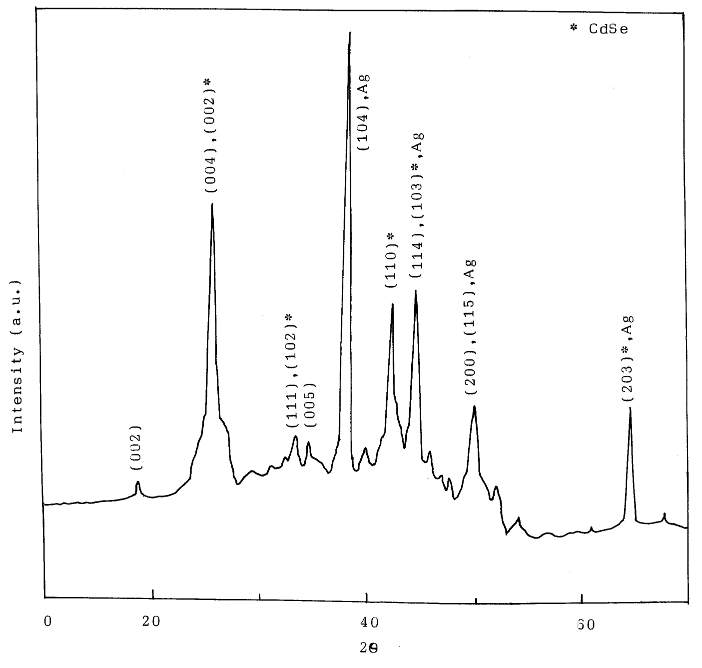

Figure 1. X-ray diffraction pattern of Ag/Hg-1212/CdSe heterostructure.

and 7.01 Å for CdSe. Full-width at half-maxima (FWHM) was measured for Hg-1212 and CdSe and by applying Scherrer's formula the particle sizes were calculated to be 24 nm and 16 nm, respectively. Figure 2 shows SEM microphotograph along the junction between Hg-1212/CdSe deposits, where two distinct granular structures with uniform and

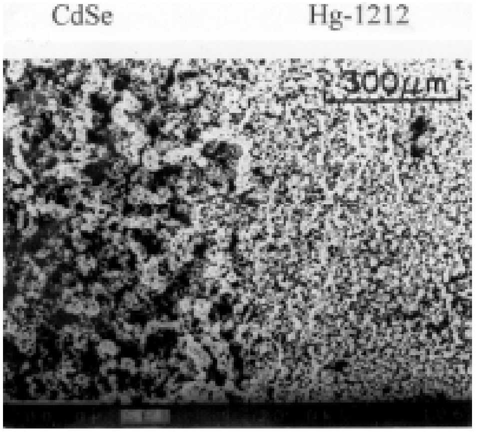

Figure 2. SEM photograph along the junction between Hg-1212/CdSe heterostructure.

non-porous regions are present. Hence, XRD and SEM studies confirm the formation of heterostructure of CdSe onto Ag/Hg-1212 film.

3.2 *TEP measurements and determination of applied bias*

The TEP measurement of individual films Hg-1212 and CdSe was carried out to study the type of carrier concentration. It was observed that Hg-1212 superconductor has p-type conductivity and semiconducting CdSe has n-type conductivity. Hence, the heterojunction formed with these deposits is metal/(p)Hg-1212/(n)CdSe.

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. 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 layers 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,

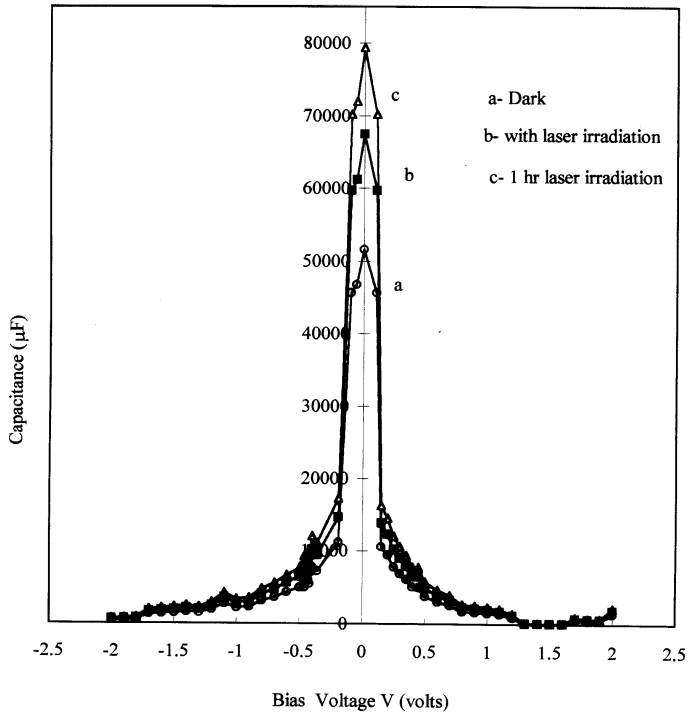

Figure 3. Plot of C–V curves for Ag/Hg-1212 junction in dark and under laser irradiation.

in the present investigation, junction capacitance of Ag/(p)Hg-1212 was measured by applying forward and reverse biased potentials, and for (p)Hg-1212/(n)CdSe and Ag/(p)Hg-1212/(n)CdSe heterojunction in reverse biased states.

3.3 *Measurement of photoinduced changes in C–V characteristics of hetero-nanojunctions*

The junction capacitance of the heterojunctions was first measured at room temperature in dark and then heterojunctions were illuminated with red He–Ne Laser (with $\lambda = 632.8$ nm, power = 2 mW and photon energy = 2.01 eV) and capacitance was measured as a function of photon dose, $Q = P \times t$ where P is the power of the laser and t is the duration of irradiation till the changes are observed.

3.3.1 *Ag/Hg-1212 heterojunction*: Figure 3 shows the plots of capacitance of Ag/Hg-1212 junction vs. bias potential. It is observed that the capacitance decreases with increase in forward and reverse bias voltage, applied across the junction. The 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

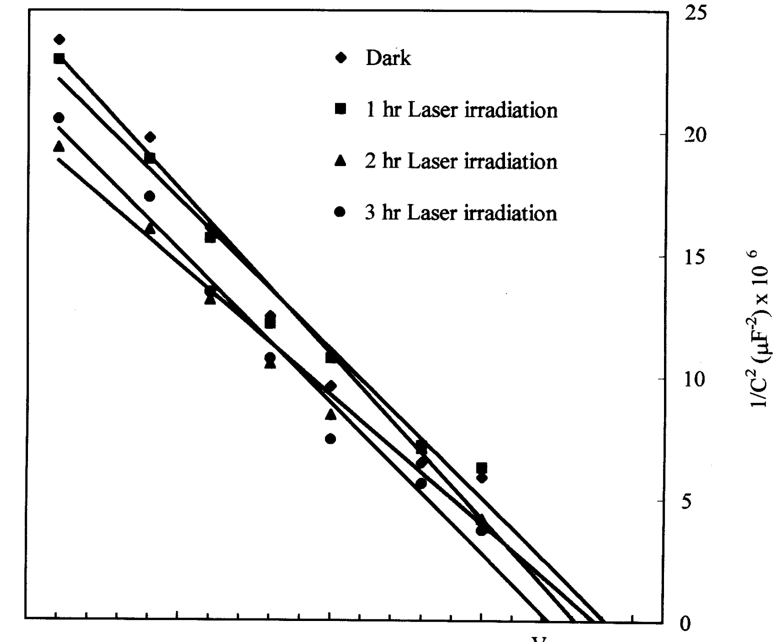

Figure 4. Mott–Schottky plots for Ag/Hg-1212 junction in dark and under laser irradiation.

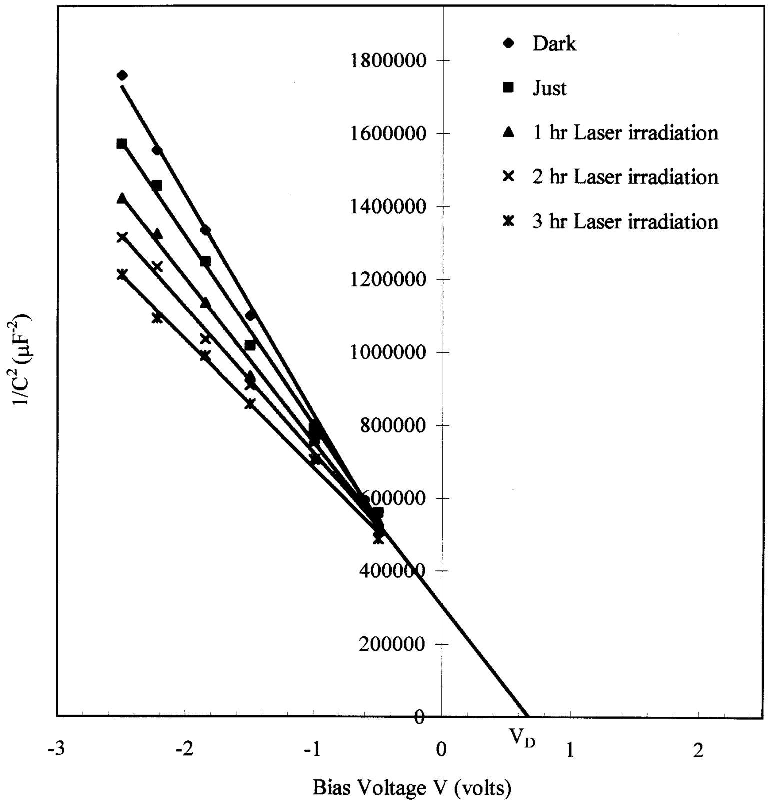

Figure 5. Mott–Schottky plots for Hg-1212/CdSe junction in dark and under laser irradiation.

$HgBa_2CaCu_2O_{6+\delta}$ and formation of insulating phase across the interface during the growth which is significant. Zdansky [16] has observed similar results on C–V measurement in metal–semi (p-GaAs) insulator junction and the results were attributed to deep level interface defects and residual impurities. When the Ag/Hg-1212 junction was irradiated with laser it is observed that the value of capacitance has increased and continues to increase with increase in the photon dose. When the superconductor, between two contacts on metal and superconductor, is irradiated with laser with photon energy 2.01 eV there is a generation of electron-hole pair at the interface, which then drifts across the junction and accumulates on the two sides. This causes an increase in capacitance.

Figure 4 shows the Mott–Schottky plot for Ag/Hg-1212 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 increase in irradiation dose. The extrapolated plots meet voltage axis at the voltage from −0.2 to −0.4 V that gives the built-in-junction potential to be 0.2 to 0.4 eV.

3.3.2 *(p)Hg-1212/(n)CdSe heterojunction*: The C–V characteristics of (p)Hg-1212/(n)CdSe junction have been measured by applying reverse biased potential, i.e., negative terminal of potential is applied to superconductor and positive terminal is applied to CdSe

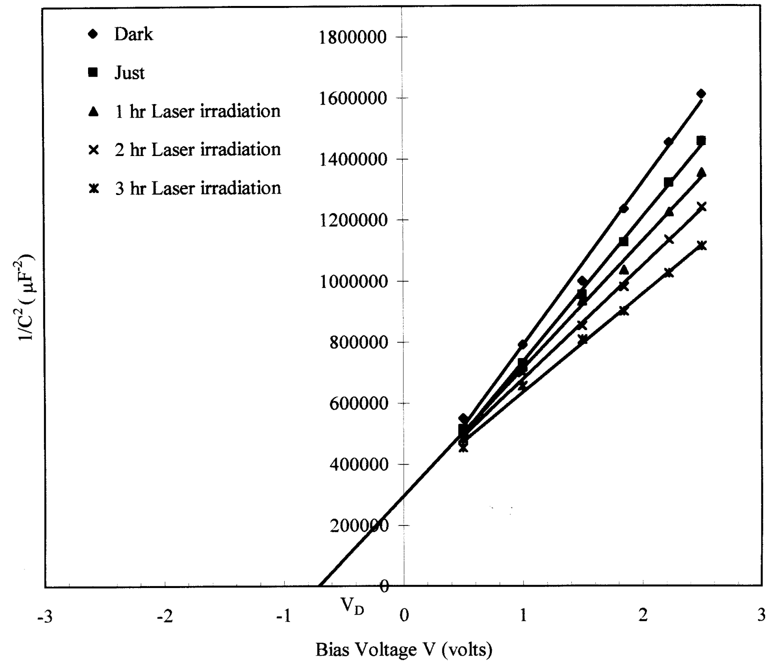

Figure 6. Mott–Schottky plots for Ag/Hg-1212/CdSe junction in dark and under laser irradiation.

film. Figure 5 shows Mott–Schottky plots for this heterojunction in dark and with photon dose. The crossover of the plot in positive voltage clearly shows abrupt p–n junction characteristics. The plot in dark condition is a straight line. The slope of the plot continues to decrease with increase in applied photon dose and attain the saturation state after about 3 h. This is attributed to 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 0.7 V, which gives built-in-junction potential to be 0.7 eV. But the increase in carrier concentration is equal in magnitude for both types of charges and hence, built-in-junction potential remains the same. This also indicates that there are no structural changes or diffusion across the junction due to laser irradiation.

3.3.3 *Ag/(p)Hg-1212/(n)CdSe heterojunction*: In this superconductor sandwiched junction, metal was given positive voltage terminal and CdSe was given negative polarity. (n)CdSe is wide band-gap (1.72 eV) material and generally its work function is higher, and hence, it forms positive space charge region. Figure 6 shows the Mott–Schottky plot for Ag/(p)Hg-1212/(n)CdSe heterojunction. The plot in dark condition is a straight line. Here also it shows the formation of abrupt heterojunction. The slope of the plot continues to decrease with increase in applied photon dose and attains the saturation state after about 3 h. The extrapolated plots meet at about the same potential −0.75 V and give the built-in-junction potential to be 0.75 eV. The magnitude of the change in slope for this junction is greater than that in the previous case, which clearly indicates that there is an increase in charge carriers in sandwiched superconductor junction due to laser irradiation.

4. Conclusion

In conclusion, pulse-electrodeposition has been used to fabricate the metal/superconductor/semiconductor hetero-nanostructures. The C–V characteristics of junctions and Mott–Schottky studies have been carried out. The increase in capacitance of heterojunction with increase in photon dose is due to increase in carrier concentration across the junction during photoexcitation.

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