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Aluminium-cadmium sulphide-aluminium thin film sandwiches were prepared by vacuum deposition techniques. Metal, cadmium sulphide and metal films were deposited sequentially on a thoroughly cleaned microscopic glass slide by using proper masks so as to form a crossed structure. The metals were deposited in a vacuum of the order of $10^{-6}$ mm of Hg. from a tungsten filament. The following method was used for cadmium sulphide deposition. Small cadmium sulphide pellets or single crystals grown by vapour deposition technique were kept in tungsten filament. After baking at 200°C for 1/2 hour in the vacuum of the order of $10^{-6}$ mm·Hg, the cadmium sulphide was deposited in the vacuum at the order of $10^{-3} - 10^{-4}$ mm of Hg. on the substrate at room temperature.

The current-voltage (I-V) characteristic was studied by using a simple circuit. A low frequency function generator and a 12 volt-battery with a variable potentiometer were used as sources. Tektronix Type A 515 Oscilloscope was used as a recorder. For measurements at various temperatures a brass sample holder with proper electrical contacts was used.

The structures (Al-CdS-Al) showed two stages. In the first (or pre-break down) stage the characteristic showed high resistance and hysteresis when the bottom electrode was made negative and the current varied non-linearly with voltage at higher voltages. After increasing the applied voltage beyond a critical point, which depends upon the thickness, the temperature and the nature of the
cadmium sulphide film; an irreversible break down took place and the structure was transformed into a second (or post-break down) stage. In this stage a new phenomenon of dual negative resistance was observed. Both the types i.e. current controlled negative resistance (CCNR) as well as voltage controlled negative resistance (VCNR) were observed in the same sample (Fig.1). The phenomenon can be described as follows: If the voltage was increased with top electrode positive then at $V_A$, the voltage across the sample suddenly dropped down to $V_B$ through AB. On decreasing the voltage from point B the path BOC was followed. At C (top electrode negative) the current dropped down to $I_D$ and the path DEDOA was obtained. The part of the curve OABO resembled the current controlled negative resistance curve with large hysteresis effects and the part of the curve OCDEO resembled the voltage controlled negative resistance with large hysteresis effects. At $V_A$, the structure transformed from low to high conductivity state while at $V_C$, the high to low conductivity state transformation took place. In both the states the current varied non-linearly with voltage in either direction. Furthermore, the switch over from one to the other state took place at the respective critical voltages only. If these critical voltages were not reached the I-V curve were retraced reversibly in the original state.

In order to understand the possible mechanism of this behaviour and the possible cause for the asymmetry in the structure some more experiments were carried out, and the following results were obtained.
The presence of either Al or In was found to be necessary for the dual negative resistance.

The effect of temperature on this behaviour was found to be more pronounced in the pre-breakdown stage. The decrease in temperature in general increased the break down voltages $V_X$ and the critical voltages $V_A$ and $V_D$. The current density increased as the temperature was decreased.

The effect of thickness on the pre-breakdown stage was found to be more pronounced than the post-breakdown stage. The $V_X$ increased with the increase in thickness.

It was thought that the thin aluminium oxide layer on bottom electrode and cadmium oxide film on CdS was responsible for the asymmetry. To confirm this Al-Al$_2$O$_3$ - CdS-Al structures were prepared by growing a thin oxide film on bottom aluminium by oxidation prior to cadmium sulphide deposition and the I-V characteristics were studied. Similar structures by growing a thin oxide layer on cadmium sulphide prior to deposition of top aluminium were also prepared and studied. Furthermore, samples were prepared without breaking the vacuum between each successive deposition. All these experiments did not change the characteristics. This shows that the phenomenon as well as the asymmetry may not be due to the surface layers.

The vacuum deposited films were heated in vacuum and sulphur atmosphere to remove possible non-stoichiometry. No effect was observed on DNR; however, small changes in the conductivity were observed in the pre-breakdown stage.
The original cadmium sulphide powder was mixed with \( \text{In}_2\text{S}_3 \) and \( \text{Ag}_2\text{S} \) and the samples were prepared. The adding up of impurities did not show any pronounced effect on the characteristic. The only effect was that sometimes for the samples doped with \( \text{Ag}_2\text{S} \) CCNR was observed where VCNR would have been in pure CdS and vice versa.

The study of the current-voltage dependence in the pre-breakdown stage shows that conduction can be explained on the basis of one carrier space-charge limited currents in presence of (i) free carriers in thermal equilibrium with traps, and donors, and (ii) shallow traps, the density of which increases as the distance from the conduction band increases.

The observed effects of different parameters on the pre-breakdown and post-breakdown stages show that the pre-breakdown stage is governed by the bulk of cadmium sulphide while in the latter stage the bulk has very small effect on the conduction. The cause for the transformation is suggested to be due to thermal or field breakdown which removes the effective trap density giving increased conductivity.

The conduction in the post-breakdown stage is explained on the basis of one carrier space-charge limited currents in presence of free carriers in the conduction band.

The observed DNR can be explained by one of the following two mechanisms:
(1) Formation of high field domains at critical voltage $V_C$ transforms the structure to low conductivity state and they are destroyed at $V_A$ transforming the structure to high conductivity state. The formation of high current filaments at $V_A$ and disappearance of them at $V_C$ also can explain the behaviour.

(2) Cadmium sulphide contains two types of centres:

(i) with high electron capture cross-section $[\text{HEC}]$ and

(ii) with low electron capture cross-section $[\text{LEC}]$. $[\text{HEC}]$ centres are effective in trapping and are distributed in the bulk of the film while $[\text{LEC}]$ are ineffective as electron traps and concentrated near the bottom electrode. To start with, both the $[\text{LEC}]$ and $[\text{HEC}]$ centres are equally populated giving a number of unoccupied $[\text{HEC}]$ centres. This is the low conductivity state. When the negative voltage on the bottom electrode is increased (at $V_A$) the tunneling of electrons from $[\text{LEC}]$ centres to $[\text{HEC}]$ centres takes place. This decreases the density of unoccupied $[\text{HEC}]$ centres giving decreased trapping and thus the conductivity increases. This is the high conductivity state.

This state remains till the voltage in the other direction ($V_C$) is reached where tunneling back from $[\text{HEC}]$ centres to $[\text{LEC}]$ centres takes place to give a situation as in the low conductivity state. In the low conductivity state the unoccupied $[\text{HEC}]$ centres are more than that in the high conductivity state and hence the trapping of injected and free carriers is more.