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Ohmic contacts to p-type $Hg_{0.3}Cd_{0.7}Te$ by metalorganic chemical vapour deposition of HgTe

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Ohmic contacts were obtained to p-type $Hg_{0.3}Cd_{0.7}Te$ crystals by metalorganic chemical vapour deposition (MOCVD) of HgTe as an interface material between the crystals and the contacting metal. Deposition at a reduced temperature of 350 °C did not lead to an obvious change in the material performance. Electronic-transport data are given. Two acceptor levels, at 4.8 and 60 meV above the valence-band edge, were found.

1. Introduction

Obtaining ohmic contacts to p-type wide-gap $Hg_{1-x}Cd_xTe$ ($x > 0.5$) is more of an art than a science. The interface between a metal and a p-type semiconductor is potential-barrier free for holes if the semiconductor band edges are flat or bend upwards at the metal junction; that is, if there is an accumulation layer of holes. Such an upbending occurs if the work function of the metal is larger than that of the semiconductor. The work function is the energy required to remove an electron from the metal surface, that is, the electron energy difference between being in a vacuum and in the Fermi level in the metal. By analogy, the work function of a semiconductor is the energy required to lift an electron from the semiconductor's Fermi level into a vacuum. In general, metal and semiconductor work functions are different and thus the Fermi levels are at different positions with respect to the common energy value in a vacuum. If both materials come into contact, the two Fermi energies have to equalize by carrier exchange. Fig. 1 shows the case where the work function of the semiconductor, Φ_{SC}, is smaller than that of the metal, Φ_M. This results in a flow of electrons from the semiconductor into the metal and hence in an upbending of the band edges. This hole-accumulation layer represents a barrier to electrons, but not to holes. Thus an electric current is able to flow through the junction region.

Contacting n-type semiconductors requires the opposite band bending, that is, an electron-accumulation layer. This is achieved by using a metal with $\Phi_M \leqslant \Phi_{SC}$. Many base metals fulfil this condition. As the Fermi level in n-type material is close to the conduction-band edge, the work function of n-type $Hg_{1-x}Cd_xTe$ does not change much with composition, that is, with band gap. Therefore, indium, for example, is appropriate as a contact material for all compositions of n-type $Hg_{1-x}Cd_xTe$.

The electron affinity, χ, of CdTe (that is, the energy difference between the conduction-band edge and a vacuum (Fig. 1)) is about 4.5 eV. Gold has a work function of approximately 4.6 eV. This means, that gold contacts are only appropriate for a maximum composition of $x = 0.2$ for p-type $Hg_{1-x}Cd_xTe$. For p-$Hg_{0.3}Cd_{0.7}Te$ a metal with $\Phi_M > 5.4$ eV is needed; this value is not delivered by any kind of metal.

2. Method and results

There have been numerous attempts to form ohmic contacts to wide-gap $Hg_{1-x}Cd_xTe$ [1, 2, 3]. The use of HgTe as an interface material to the $Hg_{1-x}Cd_xTe$ semiconductor surface was proposed by Shevchick *et al.* [4]. HgTe has a work function of approximately 5.9 eV and as a semimetal it poses no problem in forming an ohmic junction to the additionally required metal layer. Janik and Triboulet [2] obtained good results by close spacing isothermal deposition of HgTe onto p-type CdTe and $Hg_{0.3}Cd_{0.7}Te$ at 550 °C for 20 h. This resulted in a HgTe layer approximately 100 μm thick.

Here we propose a method of forming a HgTe interface layer by a metalorganic chemical vapour deposition (MOCVD) method. This method avoids excessive heat treatment of the sample as the whole evaporation process is performed at a moderate temperature of 350 °C and only lasts for several minutes [3].

MOCVD $HgTe/Hg_{0.3}Cd_{0.7}Te$ contact properties were studied on p-type $Hg_{0.3}Cd_{0.7}Te$ crystals grown by SAT, Paris, France, by a travelling-heater method (THM). The material was not intentionally doped. The ingots were sliced, chemomechanically polished

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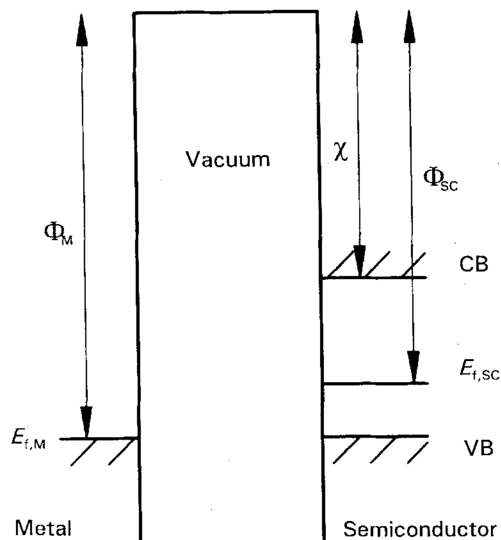

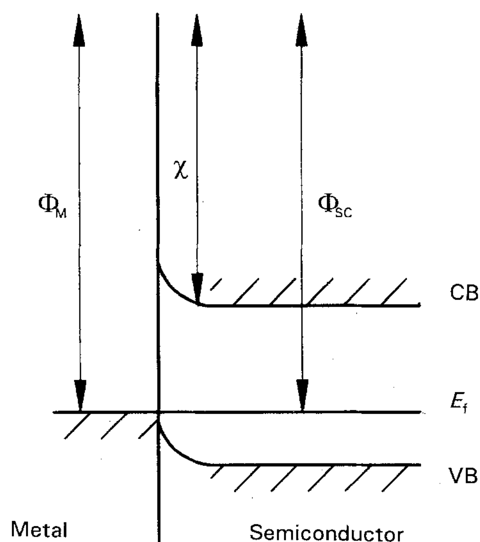

Figure 1 Energy diagram of a metal/p-type semiconductor junction. Φ_M and Φ_{SC} are the work functions of the metal and the semiconductor, respectively. χ is the electron affinity of the semiconductor: (a) the materials isolated from each other, and (b) the materials in close contact.

and annealed in a mercury atmosphere. The samples to be coated with HgTe were etched in a Br_2/methanol solution prior to the MOCVD process [3, 5]. Fig. 2 shows scanning electron microscopy (SEM) micrographs of a sample coated with an approximately 1 μm thick HgTe layer. The HgTe grows in a grain structure induced by distortions on the surface of the substrate. A typical grain size for the coating is 1 mm. Fig. 2b is a further magnification of Fig. 2a showing the smooth surface morphology of the HgTe.

For defining contacts, the surface was covered with a photoresist and exposed through a metal mask that had holes in the desired contact geometry. After taking away the non-exposed photoresist, the sample was etched to remove the HgTe, except at the contact locations. Indium was then vacuum deposited through the mask and platinum wires were soldered to the metal layer. The contacts proved to be mechan-

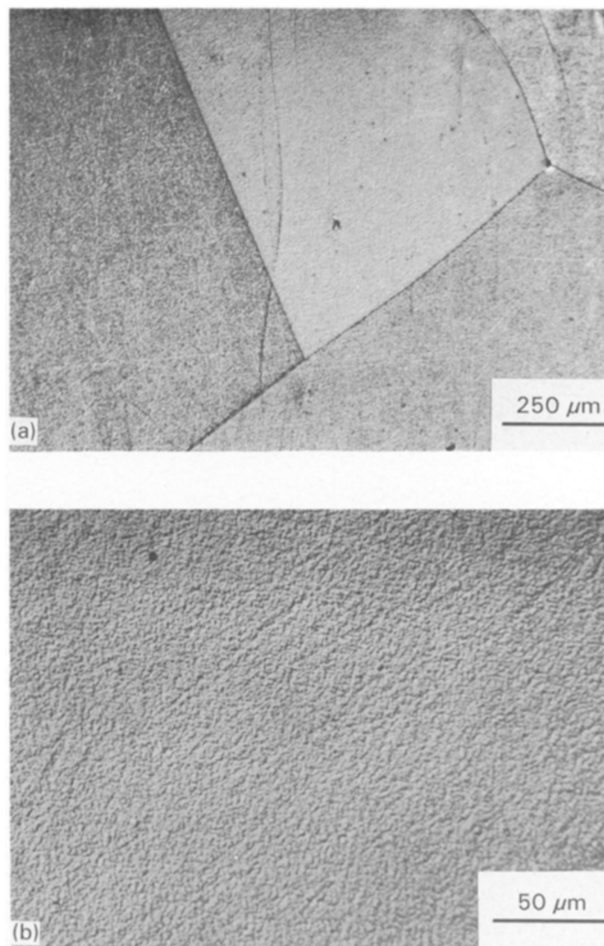

Figure 2 SEM micrographs of a HgTe-covered p-type $Hg_{0.3}Cd_{0.7}Te$ sample: (a) grain boundaries of the HgTe layer, and (b) the surface morphology of the layer.

ically and electrically stable, even after several cooling cycles down to 5 K and storage at 255 K for one year. Fig. 3 shows current–voltage (I–V) characteristics between such a pair of $Hg_{0.3}Cd_{0.7}Te$/HgTe/In contact structures. The curves also indicate ohmic behaviour in the low-temperature region.

In Figs 4 and 5 carrier concentration and carrier mobility, respectively, are shown. Hall measurements were performed by varying the magnetic field, B, in two directions, continuously between 0 and 0.3 T. The Hall voltage showed a linear dependence on B, which denotes a pure p-type behaviour. From the hole concentration as a function of reciprocal temperature, a freeze-out on a shallow acceptor level 4.8 meV above the valence-band (VB) edge can be seen. At higher temperatures the ionization of a second, deeper acceptor is observable. Its activation energy is around 60 meV. This dependence of carrier concentration on temperature is similar to that found in n-type $Hg_{0.3}Cd_{0.7}Te$ [6], where the electronic-transport behaviour is also governed by two impurities. The extremely low carrier concentration of the investigated material is remarkable. From the exhaustion plateau a net concentration of 4.5×10^{13} cm^{-3} can be deduced for the shallow impurity.

The hole-mobility values found in this material are quite high. At room temperature

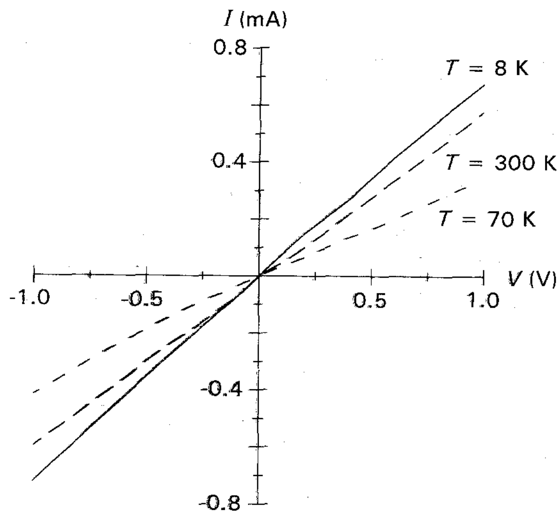

Figure 3 I–V characteristics at different temperatures between a pair of contact structures in p-type $Hg_{0.3}Cd_{0.7}Te$.

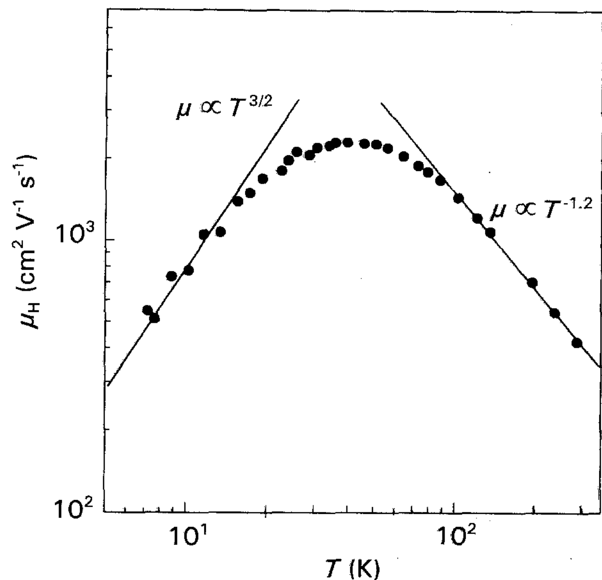

Figure 5 Hall mobility versus temperature for p-type $Hg_{0.3}Cd_{0.7}Te$.

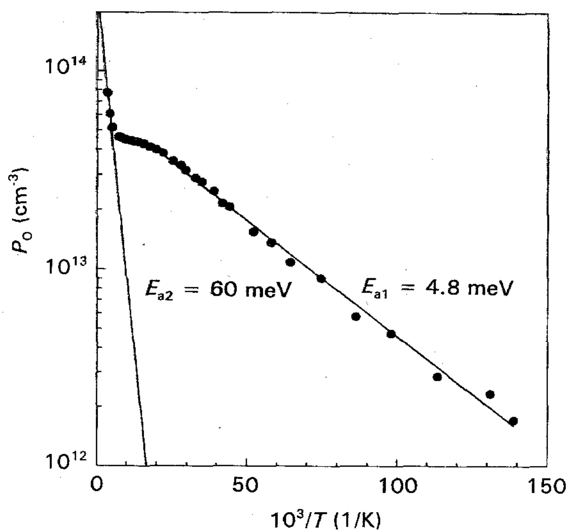

Figure 4 Carrier concentration versus reciprocal temperature for p-type $Hg_{0.3}Cd_{0.7}Te$.

$\mu = 400\,cm^2\,V^{-1}\,s^{-1}$. For $T < 40\,K$ the mobility decreases with decreasing temperature. This is probably due to impurity scattering. However, a pure $\mu \propto T^{3/2}$ dependence, which was expected for this process, was not observed. At higher temperatures, the mobility seems to be mainly governed by acoustical phonon scattering. The theoretical temperature dependence of this mechanism is $\mu \propto T^{-3/2}$. Together with scattering at polar-optical phonons with $\mu \propto T^{-1/2}$, the observed temperature dependence of the mobility can be explained.

3. Discussion and conclusions

The reason for the attempts to solve the contact problem to p-type wide-gap $Hg_{1-x}Cd_xTe$ was the need for electronic-transport data. As the I–V characteristics (Fig. 3) and the behaviour of the structures during Hall and conductivity measurements show, the proposed MOCVD coating at a temperature of 350 °C with HgTe seems to be a favourable method of achieving ohmic contacts. There is only one published paper on ohmic contacts to bulk p-type $Hg_{0.3}Cd_{0.7}Te$. This is the work of Janik and Triboulet [2], who solved the contact problem by a HgTe-deposition process associated with a thermal treatment at 550 °C. This resulted in a graded gap structure at the contact locations suppressing the interface barrier. In our case, due to the short deposition time, it is certain that no such strong interdiffusion between the HgCdTe surface and the coating, and thus no gap variation, occurred. Instead, a hole-accumulation layer just beneath the interface was formed. Photoconductivity measurements performed on the samples down to 5 K revealed that photovoltaic distortions were less than 5% of the photoconductivity signal indicating the absence of Schottky barriers [7].

In contrast to the two acceptor levels found here, Janik and Triboulet [2] saw only one impurity level at an intermediate depth of 24 meV above the VB edge. Usually, shallow acceptors of the order of 10 meV are due to mercury vacancies [8]. These shallow levels may be hidden by compensating donors. Such a compensation can also explain the extremely low hole concentration observed in our crystals. The carrier concentration in the crystals from Janik and Triboulet [2] rose by a factor of five after the HgTe-deposition process. This could be due to out-diffusion of Hg during the thermal treatment.

The contact procedure here seems not to lead to a higher carrier concentration. The measured hole concentration was even lower than the manufacturer specifies for this material at 300 K (of the order of $10^{15}\,cm^{-3}$).

In general it can be concluded that the measured properties of an MOCVD-HgTe-coated p-type $Hg_{0.3}Cd_{0.7}Te$ crystal are not much altered by the contacts. All types of transport measurements, as well as photoconductivity experiments, can be performed by using the contact structure proposed here.

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