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DIRECT EVIDENCE OF RESONANT SCATTERING AND HOT ELECTRONS STUDIES IN HgTe

C. VERIE, F. RAYMOND, J. RIOUX, A. KOZACKI and I. VACQUIE
C.N.R.S. - Bellevue
1, place A. Briand
92190 MEUDON
FRANCE

A quantitative study of A_2 acceptor level in HgTe through the fit of transport data obtained at fixed temperature is performed. Theoretical calculations take into account the band structure pecularities of HgTe together with compensation effect and resonant scattering. A broadening and a shift of the resonance level are observed and tentatively analysed. Hot electrons studies around 4.2 K lead to the evidence of free electrons scattering by resonant acceptor states and yield a first experimental evidence of the resonance width.

I. Introduction

The resonant acceptor state is one of the most interesting peculiarities of the zero gap semiconductor HgTe. The resonance conditions studies, using either a multiband Koster-Slater model [1,2,3] or an effective mass like formalism [4,5,6] showed that, in HgTe and related zero gap materials, the acceptor levels may be partially localized into resonances whereas the donor levels are overdamped. A number of previous observations of anomalies in transport properties versus temperature [7,8] and of extra transitions in magneto-optical studies [5,9] have been analyzed using the resonant acceptor state model. In the case of A_2 anomaly appearing in the conductivity versus temperature studies around 35 K an alternative explanation [10,11,12] has been proposed using an interband optical phonon scattering mechanism. On the other hand Hall effect measurements together with a plot of published experimental data versus electron concentration at fixed temperature, T=4.2 K have been interpreted on the basis of the resonant acceptor model [13]. In the present work we report a direct evidence of the A_2 acceptor level using quantitative analysis of transport data obtained on n-type doped crystals annealed with identical thermal conditions and qualitative studies of hot electrons properties in pulsed Hall effect experiments.

II. Recent studies

Recent experimental works related to A_2 resonance have been performed using magnetotransport studies [14] with the addition of hydrostatic pressure [15] or uniaxial stress [16]. The analysis of resistivity versus temperature curves show a small decrease of the conductivity for pure samples at temperatures around 35 K. This is due to an increased scattering when the Fermi energy lies in the vicinity of an acceptor resonance. The plot of the mobility versus free carrier concentration at fixed temperature for different doping conditions [14] exhibits such phenomena as soon as the Fermi energy lies in the same range. The energy value for A_2 which may computed from [14] is lower than that may be deduced in temperature dependent experiments on high mobility samples [13]. A study of transport phenomena on p-typed doped samples [17] yields values of resonant state energies which decrease as the dopant concentration increases. One of the observed levels seems to be related to A_1 whereas the other levels may be attributed to the A_2 acceptor level.

On the theoretical point of view, J.G. Broerman [18] and Zawadzki [19] studied the scattering machanisms of pure and doped HgTe. The fit of experimental data must take into account the pecularities of the band structure. At first the anomalous variation of the static dielectric constant due to interband transitions [18] and the influence of the symmetry of the carrier wave functions on the scattering mechanism. At low temperature the scattering on ionized impurities is predominant.

III. Experimental data

In the present work we have performed systematic studies of transport properties at 4.2 K on n-type doped HgTe samples prepared under carefully controlled conditions. The dopants used were either Al, Ga or In to obtain different doping levels. The samples were then annealed under temperature controlled conditions. A quasi isothermal regime was used with a cold point a few degrees below sample temperature to prevent Mercury condensation. The samples were then measured at the fixed temperature of 4.2 K in liquid Helium tank using a small electromagnet. The experimental mobility versus concentration data are summarized on Fig. (1) and Fig. (2).

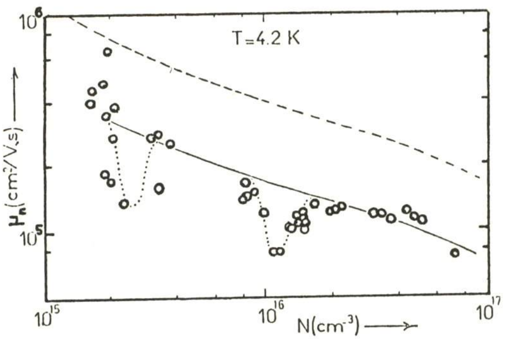

Fig.1 Mobility versus concentration for 220°C anneal
- - Calculated from [18]
—— " " [18] including Compensation effect
... computed resonance scattering

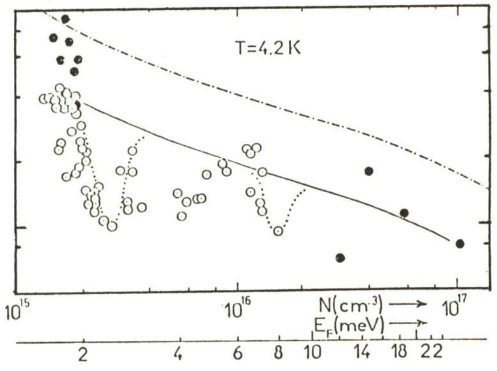

Fig.2 Same as Fig.(1) for 250°C anneal

O this work

o experimental data in [20]

The experimental points kept correspond to the highest measured mobility for each doping level to prevent spurious effects arising from dopant concentration inhomogeneities. Starting from low concentrations several regimes of μ versus N may be quoted. Below the A_1 anomaly a sharp decrease in the mobility may be observed for Fermi energies lying below A_1. Two resonances occur the energy and the depth of which vary with annealing temperature. The high concentration regime is due to scattering phenomena which happen when the Fermi energy lies above A_2 or between A_1 and A_2. Very little discrepancies have been observed between samples doped at the same concentration with the three different dopants.

IV. Discussion

The scattering mechanism dominant outside resonance range may be attributed to ionized impurities scattering. In the absence of acceptor levels the charged centers concentration is equal to the free carrier concentration. The values of the mobility which may be calculated from [18] lie above the experimental data if such an approximation is used for background mobility. To fit these values it is necessary to take into account a concentration of ionized acceptor levels proportional to the ionized donor concentration. A compensation rate $\varkappa$ is then found :

$NA_1 = x\ ND$.

The rate of compensation depends on annealing conditions :

$x_{220} = 0.33 \pm 0.04$,

$x_{250} = 0.24 \pm 0.03$.

The mobility value may be computed as :

$\mu = [(1-x)/(1+x)]\mu_o$

Where μ_o is computed from [18]. The steep variation of μ for the low electron concentrations may be accounted for by the variation of the ionization rate of A_1 as the Fermi energy is locked below A_1 by a small concentration of shallow acceptor.

The resonance A_1 and A_2 exhibit a width much larger than can be predicted from the theories developed in [4,5,6]. This width cannot be taken into account by a thermal distribution broadening effect which is 0.36 meV in our case. Such broadening may be accounted for by an impurity band formation due to wave function overlap.

$\Gamma A_1 = 0.2$ meV

$\Gamma A_2 = 0.3$ meV

A crude approximation using hydrogen-like wave function for the acceptor levels yields values of the broadening in that range. The smaller broadening of A_2 arises from the less extent of its wave function. In that case the values of the acceptor concentrations have bben computed using the compensation ratio for A_1 and the depth of the resonance on mobility for A_2.

Another striking feature is the variation of A_2 energy with the annealing temperature. Such variation has been observed in HgTe with the acceptor concentration [18]. The low value of the resonance energy observed in [14] for n-type doped samples seems to be related to the same effect. In HgTe the acceptor doping level may be varied under different annealing temperatures, which act on the Hg pressure above the sample, up to 10^{19} cm^{-3} for 500°C annealing. The polarizability of the donor states has been used in [22] in a self consistent model to account for such shift. Using this approach as a first approximation on the variation of A_2 energy in an effective mass like computation the value of the observed shift ($\Delta EA_2 = 3.5$ meV) may be found for a concentration of 5.10^{15} cm^{-3} impurity states.

All these properties definitely support an acceptor model for the A_2 anomaly and exclude the possibility of the alternative explanation in term of resonant interband scattering.

V. Hot electrons experiments

Pulsed Hall effect experiments have been performed using a 25 ns, 30 A pulser and a sampling technique with a resolution of 400 ps. The measurement have been made on some of the lowest doped samples used in previous experiments after a chemical etch reduce sample size. The variation of Hall coefficient with the applied electric field shows a monotonic decrease first due to interband carrier multiplication from the valence band to the conduction band. As soon as the quasi-Fermi level reaches the A_1 acceptor level, injection on this state occurs leading to a strong decrease of the Hall coefficient slope. At the same time a dip in the mobility versus electric field is observed. If the current is further increased injection into the conduction band resumes until it occurs in the vicinity of A_2.

A similar anomaly as that observed for A_1 resonance is observed for current values above 10^4 A/cm^2. The analysis of the energy loss rate using an empirical relation for energy relaxation in the conduction band enables to compute a first approximation of bound electron lifetimes on the acceptor levels A_1 and A_2.

The energy values of these two levels are found to be respectively 2 and 9 meV, and the lifetimes lie at about 200 ps for A_1 and 50ps for A_2. The resonance widths which may be computed from such values are smaller than those obtainable from D.C. transport experiments performed previously. The fact that the sample used were high mobility and low dopant concentration samples (10^{15} cm^{-3}) account for this difference since the resonance width is related to this concentration.

VI. Conclusions

Using systematic transport experiments, the A_2 interpretation as an acceptor level has been confirmed. A shift and a broadening of the acceptor levels A_1 and A_2 have been observed with dopant concentration. These effects are related to the acceptor concentration variation through compensation. A first approach using effective mass like wave function has been made.

Pulsed transport experiments on lowest doped samples yielded a first observation of resonance width for low dopant concentration.

VII. Bibliography

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