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MAGNETIC FIELD DEPENDENT RELAXATION TIME IN p-InSb AT LOW TEMPERATURES

J.D.N. Cheeke, G. Madore and A. Hikata*

Département de Physique, Université de Sherbrooke, Sherbrooke J1K 2R1, Québec, Canada
*Metals Research Laboratory, Brown University, Providence RI, U.S.A.

Abstract.- We have observed a magnetic field dependent relaxation time in p-InSb at low temperatures (~10K) where the electrical conduction is by free holes in the valence band. The relaxation peak is only observed in nondegenerate specimens for those acoustic modes which are piezoelectrically active. The results are compared with the acousto-electric theory of Hutson and White and found to be in substantial agreement.

There have been many recent investigations of ultrasonic absorption by shallow and deep impurity centers in semiconductors at low temperatures, in which effects characteristic of both resonance and relaxation regimes due to absorption by impurity centers have been observed [1]. Our preliminary results on p-InSb were also interpreted in this way [2]. However, more recent data on the polarisation dependence of the attenuation, taken together with the strong correlation between resistivity and attenuation results points to the piezoelectric interaction between the ultrasonic wave and free holes in the valence band as being at the origin of the observed relaxation peaks. It appears that this interaction is responsible for the magnetic field dependent attenuation in both the free and bound carrier regimes, but only the former case will be treated in this communication.

Specimens of p-InSb doped with Germanium with excess concentrations of $10^{19}$ cm$^{-3}$, $2 \times 10^{15}$ cm$^{-3}$ and $8 \times 10^{16}$ cm$^{-3}$ have been studied in the present work. The resistivity measurements were made by the conventional 4 probe method in parallel magnetic fields. The ultrasonic measurements were made using standard techniques with a Matec system and lithium niobate transducers grease bonded onto the specimen surfaces. All measurements were made in a double calorimeter with He exchange gas and a lakeshare capacitive diode in the bore of an 8T superconducting solenoid. Most of the ultrasonic work was done in perpendicular magnetic fields as the effects were rather larger than in parallel field. Velocity measurements were made only at 30 MHz for technical reasons by the pulse overlap method with a precision of about $10^{-5}$ in $\Delta v/v$.

Typical experimental results for the attenuation in zero magnetic field as a function of temperature and frequency are shown in fig.1. The scaling of the amplitude and
Figure 1

Figure 2

Figure 3

Figure 4
position of the peaks with frequency clearly establishes this as a relaxation peak. Application of a magnetic field has a dramatic effect on the peak position as indicated in fig.2, where at 30 MHz the peak is shifted by several degrees by fields of the order of a few Tesla. Velocity measurements for the same specimen in identical conditions are shown in fig.3. Again the form of the $\Delta v/v (T)$ curve is characteristic of a relaxation process and this curve is shifted in identical fashion by a magnetic field. The behaviour clearly indicates the existence of a magnetic field dependent relaxation time.

Similar measurements were made on the resistivity in this temperature and field range and these results are shown in fig.4. At the higher temperatures ($T > 7K$) we are able to identify the $\epsilon_1$ conduction regime due to free holes in the valence band. The slope of the curves in fig.4 gives a ionisation energy $\epsilon_1 \sim 10$ meV. At lower temperatures ($T < 6K$) after a possible transition through an $\epsilon_2$ impurity band regime we pass into the $\epsilon_3$ hopping conduction regime with $\epsilon_3 \sim 0.2$ meV. The general form of the results and the values of the activation energies are in good agreement with previous work on similar specimens [3]. One should also note in fig.4 that the relaxation time obtained from the usual relaxation formula and the peak position has a form similar to that of the resistivity with approximately the same activation energy $\Delta \sim 10$ meV. This indicates a very close correlation between the resistivity and attenuation mechanisms.

Besides the magnetic field dependence, important information is provided by the polarisation dependence of the attenuation peak. It is found that there is only a relaxation peak for those modes which are piezoelectrically active, that is longitudinal waves along $\{111\}$ and transverse waves along $\{110\}$ with $\{001\}$ polarisation. As the peak is always found in the $\epsilon_1$ conductivity regime, this strongly suggests that the observed effects are due to the piezoelectric interaction between the ultrasonic waves and free holes in the valence band. This interaction has been studied in great detail in the acousto-electric effect, and in fact in its simplest form the theory predicts relaxation and dispersive effects similar to those observed here, principally due to the dielectric relaxation frequency $\omega_c \equiv \sigma/\epsilon$ ($\sigma =$ electrical conductivity and $\epsilon =$ dielectric constant) associated with the free carrier space charge built up by the piezoelectric fields. This simple theory (4) gives for the attenuation $\alpha$:

$$\alpha = \frac{1}{2} \frac{K^2 \omega}{v_0} \left( \frac{\omega_c/\omega}{1+(\omega_c/\omega)^2} \right)$$

where $K^2 =$ electromechanical coupling constant $v_0 =$ sound velocity.
We are thus led to associate $\omega_c$ with $1/\tau$ of fig.4. However as noted previously (2) while the activation energies for $\tau$ and $\rho$ observed experimentally are in reasonable agreement, the field dependent prefactors are not. A detailed analysis of this point is underway but it appears that one or both of two correction factors must be considered. Firstly as stressed by several workers (5), $\sigma=1/\rho$ only for magnetic fields parallel to the current direction which means that the attenuation data must be obtained for parallel fields before an exact comparison with the simple theory can be made. Secondly the latter should be modified to take into account carrier "de-bunching" effects due to their thermal diffusion, characterized by a diffusion frequency $\omega_D=\gamma_0^2/D$ where the diffusion constant $D=\mu k_B T/q$, with $\mu=$ carrier mobility and $q=$ electronic charge. Then the modified form for the attenuation becomes (4):

$$\alpha = \frac{K^2 \omega_c}{2\omega_D} \left( \frac{1}{1+\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)^2} \right)$$

Detailed comparison with this more sophisticated treatment must await the experimental determination of the parallel field attenuation and the Hall effect under identical conditions. However a preliminary calculation using reasonable values for the mobility shows that the qualitative variation of $\alpha$ as a function of $\omega$, $T$ and $H$ as well as the order of magnitude of the peak height can be very well explained by this model.

A number of further experiments are planned in order to distinguish between this model and the impurity absorption model (2). We plan to test the latter by looking for a resonance regime at higher frequencies and lower temperatures; preliminary results at 700 MHz down to 1.3K have been negative on this point. Secondly we hope to make a quantitative test of the present free carrier absorption model by parallel field attenuation and Hall effect measurements; in this case there would be no free parameters in the theoretical expressions given above.

In conclusion available data on the ultrasonic attenuation in p-InSb at low temperatures suggests a relaxation process due to piezoelectric interaction with the free carriers. Such an effect has not been observed before at low temperatures to our knowledge; the particularity of this case as compared to the usual room temperature regime (4) is that the carrier density is extremely small, $\sim 10^{10}$ cm$^{-3}$ for $T \sim 10$K. If we obtain a quantitative verification of the model as outlined above we hope to apply the method to the determination of the electronic parameters of semiconductors, as well as to investigate the phenomenon in other piezoelectric semiconductors.
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