PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN **49** (1980) SUPPL. A p. 687–690

PHONON INDUCED INTERSUBBAND RESONANCE IN AN INVERSION LAYER

S. Komiyama, H. Eyferth and J. P. Kotthaus

Institut für Angewandte Physik
Universität Hamburg
Jungiusstr. 11, 2000 Hamburg 36
F. R. Germany

We measure the conductivity of inversion layer electrons on p-InSb as a function of electron density n_s in the presence of strong magnetic fields perpendicular to the semiconductor-oxide interface. At elevated temperatures ($T\sim 100$ K) resonant structures are observed at those n_s-values where the subband splitting coincides with the LO-phonon energy. These structures are interpreted as the E_{0-1} and E_{0-2} intersubband transitions induced by a one-LO-phonon scattering mechanism.

In a space charge layer at a semiconductor-insulator interface, the motion of electrons perpendicular to the interface is usually quantized to give discrete two-dimensional subbands. For parabolic bands, the resulting electronic energies are $E_n(\vec{k}_{/\!/})=E_n+\hbar^2 k_{/\!/}^2\,/(2m_{/\!/}^*)$, where E_n is the energy at the bottom of the n-th subband. If the electrons interact with an optical phonon of discrete energy $\hbar\omega_o$, resonance transitions of electrons between m-th and n-th subbands will take place when the splitting $E_{m-n}\equiv E_m-E_n=\hbar\omega_o$, and thus reduces the scattering time of the total electron system. At resonance one should therefore expect a structure in the conductivity. In a MIS (metal-insulator-semiconductor) structure the subband splitting E_{m-n} can be electrically tuned by variation of the electron density. Hence we call the expected resonance structure "the electro-phonon effect" in analogue to the magneto-phonon effect [1,2].

In the absence of a magnetic field perpendicular to the interface, the observation of the electro-phonon resonance is not possible for the following two resons. First, the transition between different subbands via optical phonon scattering is always possible irrespective of the magnitude of E_{m-n} because for an electron at a state $E_m(\vec{k}_{/\!/})$ there always exists a phonon with wavevector $\vec{q}$ such that $E_m(\vec{k}_{/\!/})-E_n(\vec{k}'_{/\!/})=\hbar\omega_o$ and $\vec{k}_{/\!/}-\vec{k}'_{/\!/}=\vec{q}$. Second, the density of states at the bottom of each subband ($\vec{k}_{/\!/}=0$) does not diverge in the two dimensional electron system. In the presence of a strong magnetic field perpendicular to the interface such that $\omega_c\tau>>1$ the electro-phonon effect should be observable because the energy spectrum of the subband electrons becomes completely quantized.

Here we report the first observation of the electro-phonon resonance. The effect is detected in an electron inversion layer on p-InSb. The subband structure of inversion electrons on InSb has been calculated [3] and confirmed experimentally at 77K [4]. We measure transconductance $\delta\sigma/\delta V_g$ in InSb MIS transistors as a function of electron density n_s in a temperature range 77K$\sim$140K and at various values of magnetic field B applied perpendicular to the interface. At temperatures above 100K , wefind structures in the $\delta\sigma/\delta V_g$ vs. n_s curves at those n_s values where E_{1-0} and E_{2-0} are expected to be equal to the LO phonon energy. The structure is only observed at sufficiently high fields B where $\omega_c\tau >> 1$ and dissappears at B=0. This is expected for the electro-phonon effect.

The InSb samples were fabricated at Hitachi [5] and have an insulating SiO_2 layer of thickness $d_{ox} \simeq 5500$ Å and an Al gate of area 3x3 mm^2. The acceptor concentration of the p-InSb substrate is about $2 \times 10^{13} cm^{-3}$. We measure the source-drain current at constant source-drain voltage, hence an effective conductivity σ, which is an admixture of the transverse conductivity σ_{xx} and the Hall conductivity σ_{xy}.

Fig. (1) shows the transconductance $\delta\sigma/\delta V_g$ vs. V_g at elevated temperatures and B=0. Whereas $\delta\sigma/\delta V_g$ does not change appreciably below T~80K, it decreases rapidly with increasing T at higher temperatures. Since $\delta\sigma/\delta V_g$ is directly proportional to the field effect mobility μ_{FE} at B=0, the rapid decrease in the transconductance above $T \sim 90K$ indicates that at these temperatures scattering by thermally excited phonons becomes significant. In the same temperature interval the threshold V_{th}, as determined by the extrapolation shown in Fig.(1), shifts significantly to lower V_g with increasing T. This effect is

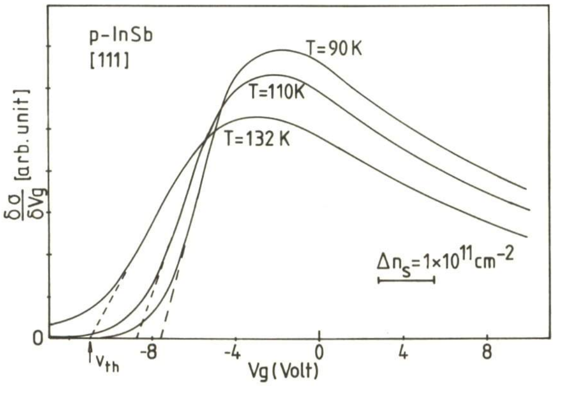

Fig.(1) Transconductance versus gate voltage for elevated temperatures at B=0. The peak mobility at 90K is $\mu_{FE} = 4.9 \times 10^4$ $cm^2/Vsec$

probably caused by a change in the occupation of surface states, because the Fermi level depends strongly on temperature at $T \sim 100K$. When we apply a strong magnetic field (9.6T) at 90K, we obtain weak SdH oscillations in the $\delta\sigma/\delta V_g$ vs. V_g curve as shown in Fig.(2). The damping of the SdH oscillations at the temperatures in Fig.(2) is determined by thermal broadening of the electron distribution rather than by lifetime broadening of the states. The latter is estimated from the mobility to be $\Delta E = \hbar/(2\tau) \sim 2.5$ meV and much smaller than the Landau splitting which is 65 meV at 9.6T. From the electron density at which these oscillations occur we tentatively assign them to the first and the second Landau levels in the lowest subband. At temperatures above 100K, the SdH oscillation are further damped. In addition relatively sharp structures appear at low densities as indicated by arrows. The structures shift towards higher V_g with increasing temperature until they are no longer discernible above 125K. Structures at nearly identical positions are also observed at B=4.7T, for example. The n_s-values at which these structures are centered are plotted versus temperature in Fig.(3). The n_s values are derived from the capacitance relation $n_s = (V_g - V_{th})\varepsilon_{ox}/(ed_{ox})$ with the threshold V_{th} determined as in Fig.(1). The arrows in Fig.(3) mark the n_s-values at which the subband splittings E_{1-0} and E_{2-0} at B=0 are expected to

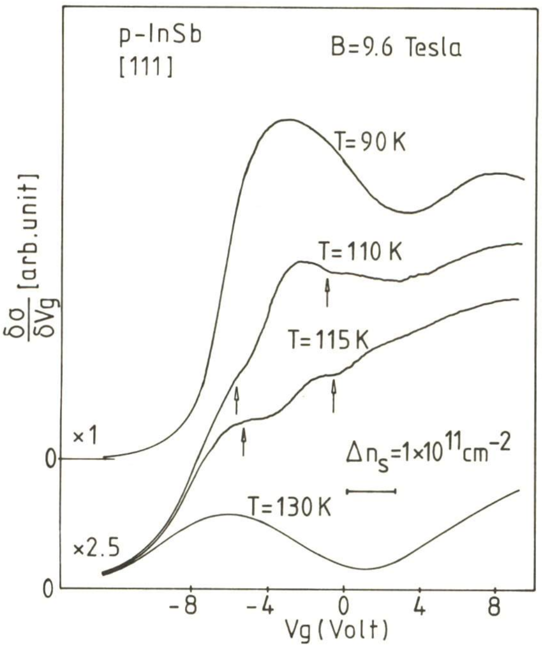

Fig. (2) Transconductance versus gate voltage at a high magnetic field B. The arrows indicate the newly observed structures

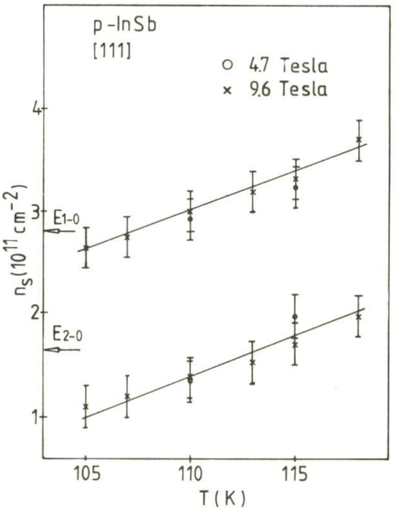

Fig. (3) Temperature dependence of the n_s values of the electro-phonon resonances: The arrows denote the n_s values at which $E_{n-o}=\hbar\omega_{LO}$ at B=O [3,4]

equal the bulk LO-phonon energy 25 meV [3,4]. The agreement with the position of the observed structures is satisfactory. This and the facts that the structures are only observed at higher temperatures and at magnetic fields where $\omega_c\tau \gg 1$ strongly support our idea that they represent the electro-phonon effect. The shape of the structures in the $\delta\sigma/\delta V_g$ vs. V_g curve corresponds to maxima in the $\delta\sigma/\delta V_g$ vs. V_g curve. With a sample geometry as used here maxima in the magnetoconductance at $\omega_c\tau \gg 1$ imply maxima in the scattering rate, consistent with the interpretation as electro-phonon effect. From the width of the structure in the $\delta\sigma/\delta V_g$ curve at e.g. 115K we estimate the energy broadening of the relevant subband states to be about 2meV which roughly corresponds to the value obtained from the mobility. The temperature dependence of the electro-phonon-resonance (Fig.(3)) is probably caused by a decrease in subband splitting with increasing temperature at fixed n_s. This is opposite to the behaviour observed in a space charge layer of Si[6]. At present we don't have a reasonable explanation for the size and the direction of the observed temperature dependence. One cause may be the thermal generation of bulk carriers at these temperatures. Similarly it is not clear why the structures disappear so rapidly with increasing temperature. These effects require further investigation.

In conclusion we believe to have obtained strong experimental evidence that the here reported structures in the transconductance manifest indeed the first observation of the electro-phonon effect.

We wish to thank Dr. Y. Shiraki of the Hitachi Central Research Laboratory for providing us with the samples. He also gave us useful comments on the present work.

References:

1) See e.g. P. G. Harper, T. W. Hodby and R. A. Stradling: Prog. Phys. 36 (1973) 1.

2) D. C. Tsui, Th. Englert, A. Y. Cho and A. C. Gossard: Phys. Rev. Letters, 44 (1980) 341.

3) K. Arai and Y. Uemura: to be published.

4) K. Wiesinger, W. Beinvogl and F. Koch: Proc. 14th Int. Conf. on the Physics of Semiconductors, 1978, P. L. H. Wilson, ed. (Institute of Physics, London, 1979) 1215.

5) N. Kotera, Y. Katayama, K. Komatsubara: Phys. Rev. B5 (1972) 3065.

6) P. Kneschaurek and J. F. Koch: Phys. Rev. B16 (1977) 1590.