[23]P. Solomon and N. Klein, J. Appl. Phys. 47, 1023 (1976).
[24]C. Falcony, Doctoral dissertation, Lehigh University, 1980 (unpublished).
[25]P. M. Solomon and D. J. DiMaria, J. Appl. Phys. 52, 5867 (1981).
[26]T. N. Theis, J. R. Kirtley, D. J. DiMaria, and D. W. Dong, unpublished.

Magneto-Polarons in a Two-Dimensional Electron Inversion Layer on InSb

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In electron inversion layers on InSb the cylotron resonance energies and linewidths are found to exhibit a marked discontinuity in the vicinity of the bulk longitudinal-optical-phonon energy. These features are attributed to resonant electron-phonon interaction in the two-dimensional electron system. The experimentally observed mass discontinuity indicates that the electron–optical-phonon interaction in a two-dimensionally confined electron system is enhanced in comparison to the three-dimensional case.

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Here we report on the observation of magneto-polaron effects in a two-dimensional electron system (2DES) that is created by field effect[1] at the semiconductor-oxide interface in a metal-oxide-semiconductor (MOS) structure on p-InSb. In our experiments we investigate the frequency dependence of the cyclotron resonance (CR) of inversion-layer electrons at discrete laser energies below and above the reststrahlen region. Resonant electron-phonon interaction is observed to cause discontinuities in the cyclotron energies and linewidths of Landau transitions in different electric subbands as the laser energy is varied from below to above the longitudinal optical (LO) phonon energy. Our investigations constitute the first clear experimental evidence that the two-dimensional confinement of the electron system causes a significant enhancement of the electron–optical-phonon interaction.

The nature of the electron–optical-phonon coupling in systems of reduced dimensionality in polar semiconducting materials has recently attracted much theoretical interest[2,3] and a variety of aspects of the surface polaron problem have been pointed out. An electron near the surface of a polar material not only couples to bulk LO phonons, but also may interact with surface optical phonons and purely two-dimensional optical-phonon modes. It has been argued that the presence of the interface makes it possible for phonons with arbitrary wave vectors perpendicular to the surface to participate in the interaction process.[2] This may alter the self-energy correction as compared to the bulk case. Because of the complete quantization of a two-dimensional electron gas in the presence of a magnetic field, the resonant interaction of Landau electrons with LO phonons is also expected to be much sharper than in the bulk.

In inversion layers of MOS structures the electron motion normal to the surface is quantized in electric subbands E_i as a result of the surface electric field, while the electrons are free to move parallel to the surface.[1] If a magnetic field B is applied perpendicular to the surface the parallel motion becomes quantized in Landau levels n. With neglect of electron spin, the energy spectrum is given by $E_{i,n} = E_i + \hbar\omega_{i,n}(n+\frac{1}{2})$ where $\omega_{i,n} = eB/m_{i,n}$ and $m_{i,n}$ is the frequency-dependent cyclotron mass of the n to $n+1$ Landau transition in the subband i.

Since CR in n-InSb has successfully been used to study volume magneto-polarons,[4,5] and surface CR in inversion layers on InSb has been investigated previously[6,7] to determine CR masses in their dependence on electric subband index and inversion electron density, CR seems best suited also to obtain information on the electron–optical-phonon interaction in a 2DES. For such experiments it is vital to fabricate MOS structures with very high inversion-layer mobilities to be able to extract the relatively small polaron effects. The substrates of our MOS capacitors are Ge-doped ($N_A \simeq 10^{14}$ cm^{-3}) p-type InSb(111) platelets with a typically 400-nm-thick SiO_2 gate insulator[8] and a semitransparent NiCr gate contact.

The experimental techniques are similar to those in previous reports.[6,7] Some of the present experiments are also performed in tilted magnetic fields, i.e., the magnetic field vector is tilted by an angle Θ from the direction normal to the inversion layer. Surface CR is observed in the relative change in transmission $\Delta T/T = -[T(V_g) - T(V_{th})]/T(V_{th})$ where V_g is the gate voltage and V_{th} the inversion threshold. The latter is determined from the onset of the high-frequency field-effect mobility $d\sigma(\omega)/dV_g$ which is proportional to dT/dV_g.[9] At electron densities $> 10^{11}$ cm^{-2} the mobile-electron density n_s is determined from Shubnikov–de Haas (SdH) experiments[1] at microwave frequencies. At densities $n_{ind} \lesssim 10^{11}$ cm^{-2} where it is not possible to observe SdH oscillations clearly, the mobile-electron density is extracted from the integrated CR intensity[7] and is significantly lower than the induced-electron density.

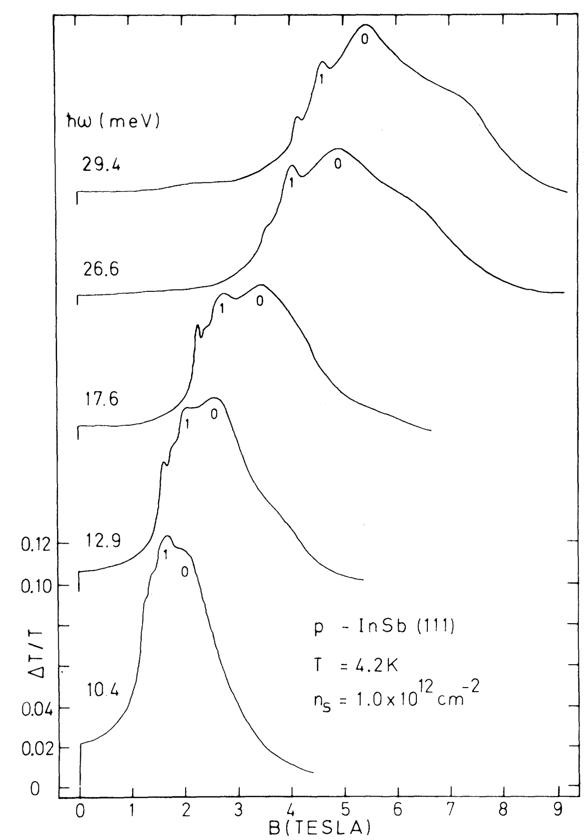

FIG. 1. CR traces for various laser energies below and above $\hbar\omega_{LO}$ = 24.4 meV. Subband CR's are indicated by the subband indices 0 and 1. The structures on the low-field side are impurity and bulk-electron resonances. The shoulders at the high-field side are quantum oscillations.

At high electron densities typical CR spectra as shown in Fig. 1 for various laser energies $\hbar\omega$ below and above the LO-phonon energy $\hbar\omega_{LO}$ are rather complicated. To extract the desired information on the electron–optical-phonon interaction, identification of the individual peaks in Fig. 1 is necessary. Figure 2 shows the dependence of the CR signal on electron density n_s and tilt angle Θ at a laser energy $\hbar\omega < \hbar\omega_{LO}$. The CR maxima at high magnetic fields B shift with density as is known for subband CR in InSb,[6,7] and depend on tilt angle as is expected for surface CR.[9] In contrast, the resonance positions of the sharp peaks at low magnetic fields depend neither on density nor on tilt angle within the precision of our measurements ($\Delta m = \pm 0.0002$). The peak at $B = 2.25$ T lies below the bulk electron CR of InSb and changes its intensity with gate voltage V_g. From fits to the line shape we find that the corresponding states start to be filled at about the threshold voltage and are filled to a maximum density of about 1.5×10^{10} cm^{-2}. Therefore we

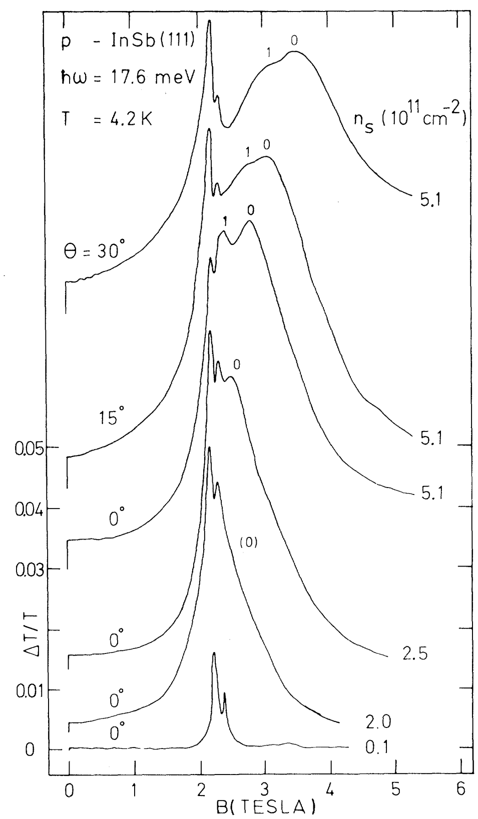

FIG. 2. CR traces for various densities n_s and tilt angles θ. The structures at $B = 2.25$ and 2.39 T are impurity and bulk-electron resonances, respectively.

interpret this peak as a surface-bound–impurity transition. The intensity of the small peak at $B =$ 2.39 T does not significantly depend on gate voltage, its width corresponds to a mobility of $3\times10^{+5}$ $cm^2\ V^{-1}\ s^{-1}$, and its position always coincides with the one of bulk CR in n-InSb.[10] This leads us to interpret it as a gate-voltage–induced conduction-band CR. This is surprising since the substrate is p type, as is confirmed by the observation of a gate-voltage–independent CR signal of bound holes[11] in the transmission T. However, from our fits to the CR signals such as in Fig. 2 we find that below $n_s \simeq 1\times10^{11}$ cm^{-2} a large fraction of the induced electrons is trapped in surface states. Probably, slow charging of at least part of these states as the gate voltage is square-wave modulated at typically 10 Hz leads to a small current of bulk electrons. This may cause the small bulk CR signal that corresponds to an electron density of about 5×10^9 cm^{-2}. No bulk-electron signal can be detected above $\hbar\omega_{LO}$ in our experiments (see Fig. 1). This may be explained by the bulk-electron–LO-phonon interaction[5] that is expected to increase the linewidth of the bulk-electron signal by a factor of 5.

Because of the relatively high mobility in our samples the resonant magnetic fields of the CR transitions discussed above, i.e., the cyclotron masses, can be read from the positions of the maxima in traces like those in Figs. 1 and 2. The thus-obtained frequency dependence of the CR masses is shown for two densities in Fig. 3. For comparison, volume conduction-electron masses[5] are included in Fig. 3 as solid lines.

In Fig. 3, all masses show marked discontinuities near the bulk LO-phonon energy $\hbar\omega_{LO}$. Whereas in bulk n-InSb the discontinuous changes of the cyclotron mass at $\hbar\omega_{LO}$ for conduction electrons and impurities are reported to be identical,[5] the discontinuity for the field-effect-induced impurity transition observed here is enhanced by about a factor of 3 at $\hbar\omega = 26.6$ meV, which is the closest energy to $\hbar\omega_{LO}$ in our experiments.

The CR masses of the ground and first excited subband, m_0 and m_1, respectively, exhibit discontinuities that are significantly enhanced as compared to the bulk case. The general increase with frequency reflects the nonparabolicity of the electric subbands. Deviations from this general behavior (see Fig. 3) are relatively small and are probably caused by quantum oscillations,[9,12] which also have been found to be responsible for the broad structures on the high-field side of the

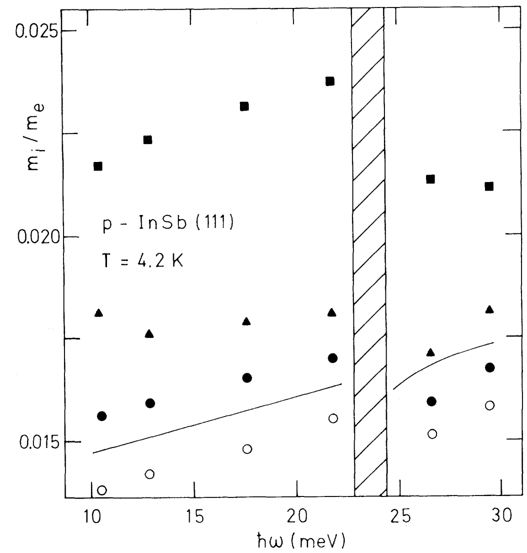

FIG. 3. Frequency dependence of CR masses for subband and impurity (open circles) transitions for two densities n_s. At $n_s = 2\times10^{11}$ cm^{-2} only masses of the ground subband (solid circles) are observed, whereas at $n_s = 1\times10^{12}$ cm^{-2} in addition to the ground subband masses (squares) the masses of the first excited subband (triangles) are observed. The masses as determined from the resonant fields are accurate to about $0.0002\,m_e$. For comparison, the conduction-band masses of bulk InSb are given as solid lines (after Ref. 5). The reststrahlen band of InSb is indicated by the hatched region.

traces in Fig. 1.

Discontinuities in the linewidths[7] are observed as an increased broadening only at $\hbar\omega = 26.6$ meV. This is consistent with theoretical predictions,[2] where the resonant interaction of the totally quantized two-dimensional Landau electrons is expected to be sharper than in the bulk case.

Quantitative comparison with theory would be desirable to get a more detailed insight into the nature of the electron–LO-phonon interaction in two-dimensionally confined electron systems and its effect on the electron energies. The influence of screening should be incorporated, as is suggested by recent studies of the cyclotron splitting in $GaAs$-$Ga_xAl_{1-x}As$ heterostructures[13] and $Hg_{1-x}Cd_xTe$ MOS structures[14] which are claimed to provide evidence of a reduced electron–LO-phonon coupling in such 2D systems. At present we may not even speculate on the relative change of the polaron self-energy with increasing electron density, because both the 2D polaron effect and the 2D screening effect are expected to depend on density.

To summarize, we have found polaron effects in the CR absorption of inversion electrons in InSb via discontinuities in the CR masses and linewidths near the bulk LO-phonon energy. The resonant self-energy correction of the two-dimensionally confined electrons is enhanced as compared to that of the bulk electrons, indicating an enhanced electron–optical-phonon interaction near the surface of a polar semiconductor.

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[1]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. 54, 437 (1982).
[2]S. Das Sarma and A. Madhukar, Phys. Rev. B 22, 2823 (1980).
[3]T. S. Rahman, D. L. Mills, and P. S. Riseborough, Phys. Rev. B 23, 4081 (1981).
[4]D. H. Dickey, E. J. Johnson, and D. M. Larsen, Phys. Rev. Lett. 18, 599 (1967).
[5]C. J. Summers, P. G. Harper, and S. D. Smith, Solid State Commun. 5, 615 (1967); C. J. Summers, R. B. Dennis, B. S. Wherrett, P. G. Harper, and S. D. Smith, Phys. Rev. 170, 755 (1968).
[6]A. Daerr, J. P. Kotthaus, and J. F. Koch, Solid State Commun. 17, 455 (1975).
[7]M. Horst, U. Merkt, and J. P. Kotthaus, Surf. Sci. 113, 315 (1982).
[8]U. Mackens and U. Merkt, Thin Solid Films 97, 53 (1982).
[9]G. Abstreiter, J. P. Kotthaus, J. F. Koch, and G. Dorda, Phys. Rev. B 14, 2480 (1976).
[10]J. R. Apel, T. O. Poehler, C. R. Westgate, and R. I. Joseph, Phys. Rev. B 4, 436 (1971).
[11]R. Kaplan, Phys. Rev. Lett. 20, 329 (1968).
[12]T. Ando, J. Phys. Soc. Jpn. 38, 989 (1975).
[13]G. Lindemann, W. Seidenbusch, R. Lassnig, J. Edlinger, and E. Gornik, in Proceedings of the Sixteenth International Conference on the Physics of Semiconductors, Montpellier, France, 1982 (to be published).
[14]J. Scholz, F. Koch, J. Ziegler, and H. Maier, to be published.

Nonlinear Conductivity and Noise in the Quasi One-Dimensional Blue Bronze $K_{0.30}MoO_3$

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Nonlinear electrical conductivity associated with a large noise voltage has been observed in the semiconducting charge-density-wave state of the blue bronze $K_{0.30}MoO_3$. A well defined and strongly temperature-dependent threshold field for the onset of the nonlinear conductivity is found. Both broadband noise and quasiperiodic noise are detected above the threshold field. These results, including the observation of long relaxation times, are discussed in relation with the current models for charge-density-wave transport.

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Much effort has been devoted these last years to the study of the nonlinear transport properties of two transition-metal trichalcogenides, $NbSe_3$ (Ref. 1) and TaS_3.[2] These compounds are quasi one-dimensional metals at room temperature and show Peierls transitions related to charge-density-wave (CDW) instabilities below. In the CDW state, the conductivity is non-Ohmic above a sharp threshold electric field E_t. In the nonlinear regime, both broadband and so-called narrow-band noise involving well defined frequencies and their harmonics have been found.[3] These results support a model of a new type of collective transport due to the sliding of the CDW, related to either a depinning[4] or a tunneling[5] of the CDW. Up to now, the search for similar effects in other classes of compounds had been unsuccessful.

We report now the observation of nonlinear conductivity occurring above sharp threshold fields as well as of broadband and quasiperiodic noise in a transition-metal oxide, the so-called blue bronze $K_{0.30}MoO_3$. In addition to properties similar to those of $NbSe_3$ and TaS_3, we have observed, close to the threshold field, an intermittent regime of voltage pulses, with a time scale of the order of 1 s, and in all cases time-dependent effects suggesting the importance of metastable states. We propose that these properties are due to the sliding of the CDW under the effect of the