PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN **49** (1980) SUPPL. A p. 955–958

DEVELOPMENTS IN SUBBAND SPECTROSCOPY

H.R. Chang, H. Reisinger, F. Schäffler,
J. Scholz, K. Wiesinger, and F. Koch

Physik-Department E 16, Technische Universität München
8046 Garching, Fed. Rep. of Germany

We survey current work and some results of infrared absorption spectroscopy on Si, Ge, InSb, and InAs. Emphasis is on the common features.

The resonant excitation of semiconductor surface bands by the absorption of infrared radiation is an established experimental probe of the interfacial charge layer. Transitions, such as sketched in Fig. (1), from an occupied subband $E_o(k_{\parallel})$ to a higher-lying $E_1(k_{\parallel})$ are recorded as an absorption peak in a sweep of surface charge density N_s or the excitation energy $\hbar\omega$. A subband splitting E_{o1} results in a measured resonance energy $\tilde{E}_{o1}$ which contains the contribution of the depolarization effect and an exciton-like final state interaction.

Originally subband resonance was conceived as a low T experiment. With frequency $\hbar\omega$ chosen sufficiently high, it has since proved possible to follow a distinct set of resonances in Si (100) to 300 K and above [1]. Fig. (2) is a set of such curves for $\hbar\omega$ = 30.2 meV. The

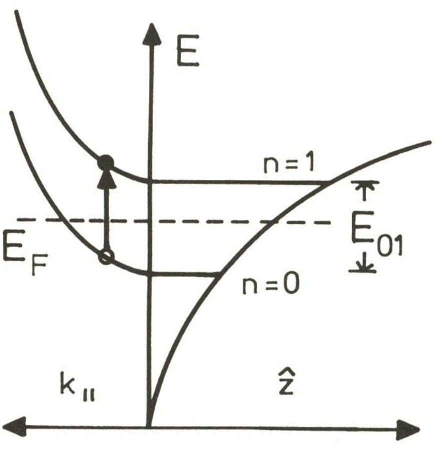

Fig.(1) Subbands $E_n(k_{\parallel})$ and levels in the surface potential well. Transitions lead to an observed peak at $\tilde{E}_{o1}$

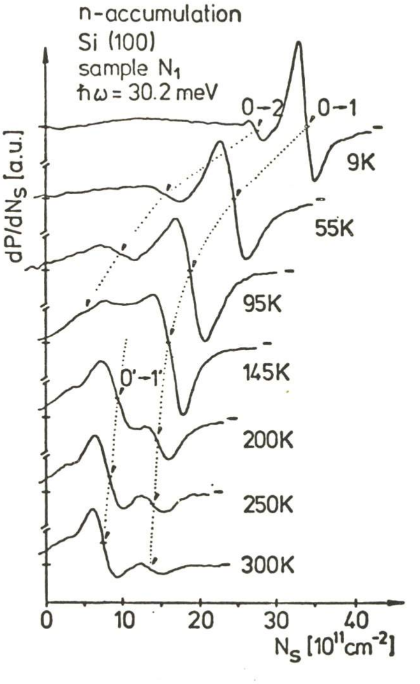

Fig.(2) Subband resonances in Si (100) to 300 K appearance of new lines (for example 0' → 1') from thermally occupied levels and the position shifts have been discussed. Of particular interest for the work to 300 K has been the identification and measurement of a T-dependence of the optical linewidth. With rising T there is found an increasing energy width of the resonances, one that derives from a larger $\Delta E_{01}/\Delta N_s$ at higher T. The linewidth increase is less than that expected from the T-variation of the transport lifetime. Evidence from a comparison of the N_s- and T-dependences, as well as from an examination of different samples, points to a lack of correspondence of transport mobility and optical lifetime.

In other work on the electron subbands on (100) Si we are examining the influence of Na^+ ions on the resonance. The first such work has been reported in ref. [2]. We have examined in particular the dilute range of Na^+ concentration (0 - 1 x 10^{11} Na^+cm^{-2}). Work on the surface cyclotron resonance [3] shows in particular strong broadening of the resonance already for a few 10^{10} Na^+cm^{-2}. In this limit the Na^+ ions appear homogeneously distributed, a fact that is substantiated by C-V studies (4.2 - 300 K). By comparison, the 0 → 1 subband transition does not broaden and remains fixed in position relative to the 4.2 K flat-band voltage. The oscillator strength of the distinct transition diminishes rapidly with Na^+ concentration at the expense of a broad absorption at lower N_s. The experiments provide a first understanding of the peculiar sample-dependent variation of the relative oscillator strengths of the 0 → 1 transition and the broad precursor absorption discussed in Fig.(9) of ref. [3]. These observations illustrate again that optical width and transport lifetime are not directly related.

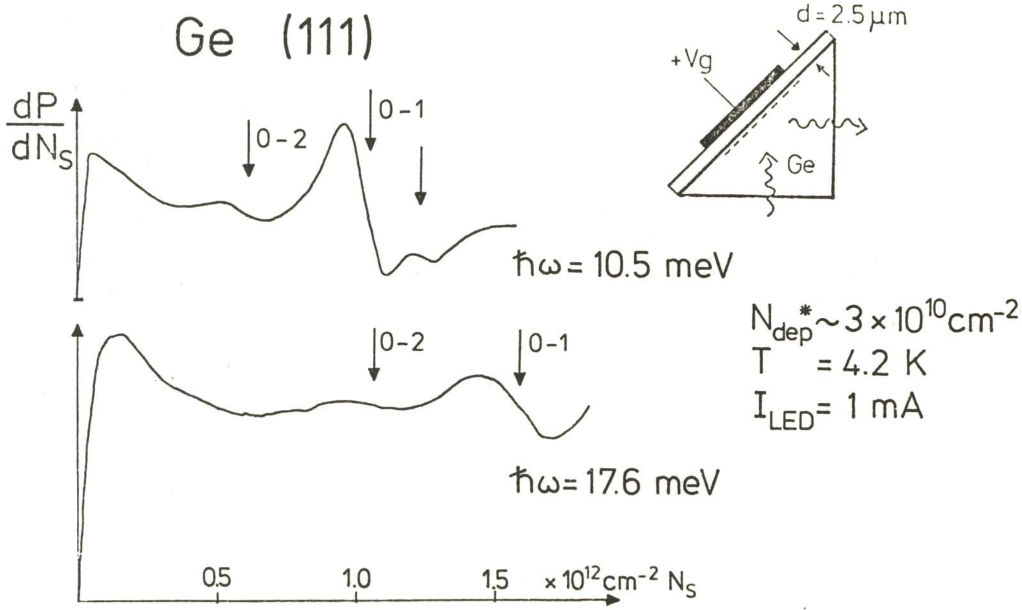

Fig.(3) Subband resonance on Ge: Note the doublet structure of the 0 → 1 transition in the upper trace

The question of optical width and transport mobility is also encountered in the work on Ge (111) surfaces. Previous work [4] has been extended to additional frequencies but is limited to $N_s \sim 2 \times 10^{12} cm^{-2}$ because of breakdown of the lacquer insulator. Work with thermally ($T \sim 350^o$ C) deposited SiO_2 allows $N_s \sim 5 \times 10^{12} cm^{-2}$ but destroys the interfacial surface quality. No signals have been observed for electrons on (100) and (110) Ge, in spite of considerable effort. The resonances in Fig.(3) appear on top of a "parallel-conductivity" background that stems from the in-plane component of the rf field. The parallel component increases with frequency. Evaluating this Drude background absorption, as well as related Shubnikov-de Haas and cyclotron resonance measurements, we estimate a lifetime $\tau'' = 0.7 \times 10^{-13}$sec. The energy widths of the transitions in Fig.(3) are $\Delta E_{01} \simeq 2$ meV. The optical lifetime τ, calculated according to $\Delta E_{01} = (2/\sqrt{3})\Gamma_{01} = (2/\sqrt{3})(\Gamma_0 + \Gamma_1) = 4\hbar/\sqrt{3}\,\tau$, is $\sim 8 \times 10^{-13}$sec! The resonances are much sharper than expected from transport mobility. The Ge $0 \rightarrow 1$ transition, in particular the lower $\hbar\omega$ trace of Fig. 3, shows a doublet structure.

Doublets are a fact of life for InSb resonances [5]. Both the $0 \rightarrow 1$ and $0 \rightarrow 2$ transitions in the frequency sweep data of Fig.(4) show up as doublets of roughly equal strength. The continuous frequency sweep demonstrated here has distinct advantages for the evaluation of data and comparison with theory. The trace is produced from the logarithmic difference voltage of signal and source intensities measured simultaneously. We have in ref. [5] attributed the doublet to the appearance of both the shifted resonance at $\tilde{E}_{01}$ and a resonance at the subband splitting E_{01}. There are reasons for why the latter can appear with finite oscillator strength.

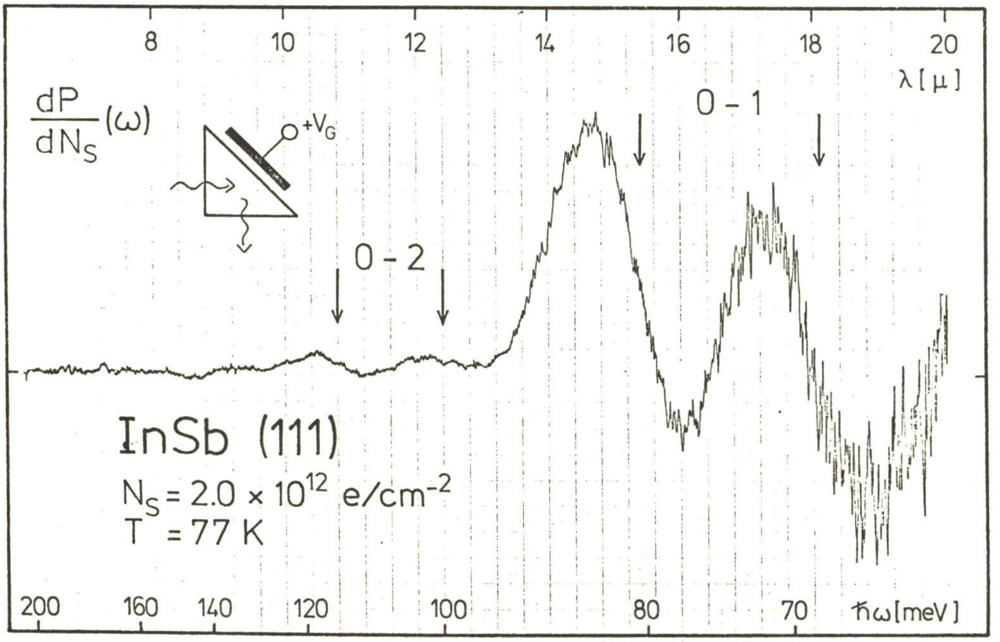

Fig.(4) Subband resonances in InSb as observed in a frequency sweep at fixed N_s: The doublet peaks are thought to represent $\tilde{E}_{01}$ and E_{01}

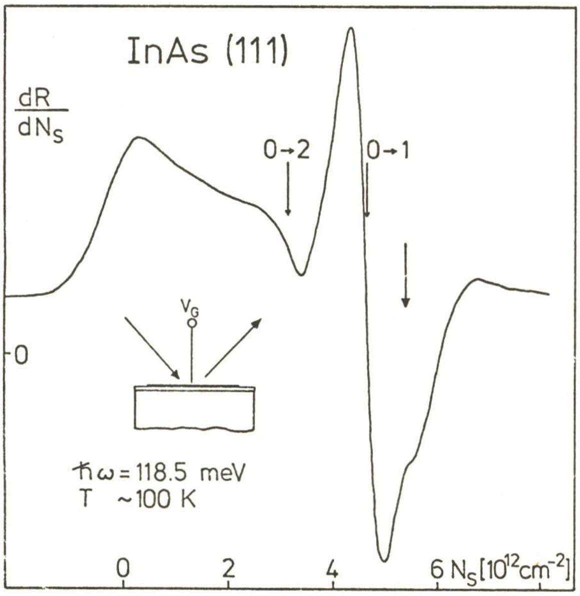

Fig.(5) Subband resonance observed in reflection from an InAs ($n = 2.1 \times 10^{16} cm^{-3}$) surface. The doublet $0 \rightarrow 1$ structure is similar to that for Ge and InSb

The newest addition to the subband spectroscopy repertoire is InAs [6]. Tunneling experiments in ref. [7] had not only given the first direct demonstration of the existence of surface subbands in this material but had also indicated that energies would be in the CO_2-laser range. Using a tunable laser ($110 \leq \hbar\omega \leq 138$ meV) we show here the InAs (111) spectrum as observed in reflection (45°) from an n-type, degenerate crystal with $n = 2.1 \times 10^{16}$ cm^{-3}. The sample has been prepared with a CVD layer of SiO_2 with thickness of a few thousand Å. The gate is a semitransparent Ni-Cr layer. In ref. [6] data for a wider range of frequencies are reported, and the doublet $0 \rightarrow 1$ transition is identified more clearly. The structure on the high-N_s side is shown to agree with E_{01} as obtained independently from Shubnikov-de Haas and cyclotron resonance experiments on the sample.

In this look at developments in subband spectroscopy we have shown that such experiments can provide microscopic, detailed information at all relevant temperatures. We have pointed to some of the difficulties in relating linewidths to transport mobilities. The long-standing problem of the appearance of doublet peaks has been compared in the resonances of Ge, InSb, and InAs. The evidence is in favor of an interpretation as $\tilde{E}_{nm}$ and E_{nm}.

References

1) F. Schäffler and F. Koch: Sol. State Commun., submitted for publication.
2) B.D. McCombe and D.E. Schafer: Proc. 14th Int. Conf. on Physics of Semiconductors, Edinburgh (1978), p. 1227.
3) P. Kneschaurek, Avid Kamgar and F. Koch: Phys. Rev. B 14 (1976), 1610.
4) J. Scholz and F. Koch: Sol. State Commun. 34 (1980), 249.
5) K. Wiesinger, W. Beinvogl and F. Koch: Proc. 14th Int.Conf.on Physics of Semiconductors, Edinburgh (1978), p. 1215.
6) H. Reisinger and F. Koch: Sol. State Commun., submitted for publication.
7) D.C. Tsui: Phys. Rev. Letters 24 (1970), 303.