Mechanism of intersubband resonant photoresponse

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We argue that the intersubband resonance observed in the dc conductivity of p-Si(100) MOSFET (metal-oxide-semiconductor field-effect transistor) devices is a bolometric response and cannot properly be described as a photoconductivity effect. The process involves resonance heating of the electrons and a temperature-dependent channel conductivity. After a discussion of the electron-bolometer model, we present results on the sign, the magnitude, the source-drain voltage dependence, the density dependence, and the temperature and magnetic field dependences of the resonance signal.

I. INTRODUCTION

Transitions between the subband levels of inversion-layer electrons on (100) p-type Si have been observed as changes $\Delta\sigma$ of the dc conductance of a metal-oxide-semiconductor (MOS) device.[1] The discrepancies between subband energies in the photoresponse and absorption spectroscopy experiments[2] have been resolved.[3-5] When proper equilibrium of the depletion and inversion-layer charges is achieved, energies are in agreement. The present considerations apply to photoresponse under equilibrium conditions.

The photosignal has been reported as negative,[1,3,4] i.e., the conductivity is decreased at resonance. This fact has figured in the construction of models for the response mechanism. In general we consider the photoresponse as

$$\Delta\sigma = \Delta n_s(e\mu) + (n_s e)\Delta\mu \,. \tag{1}$$

In published literature[1,6] the first term, with Δn_s, the number of electrons photoexcited to an upper level, has been stressed. This upper level is variously taken as a low-mobility higher subband involved in the transition,[1] the 0′ subband of the fourfold degenerate valley system,[6] or a long-lived surface trap level.[7] μ stands for the mobility reduction of the Δn_s electrons in this "photoconductivity" approach.

As an alternative, it has been suggested[8] to attribute the signal to the second term in Eq. (1). n_s is the total number of inversion electrons and $\Delta\mu$ is the decrease of their mobility induced by resonant absorption heating. The "bolometry" approach is based on the known, sensitive dependence of σ on T. With the absorption of energy, the electron temperature rises by $\Delta T_{\rm el}$ relative to the lattice. In the coupled system of electrons and lattice there is also an increase $\Delta T_{\rm lat}$ of the sample above the thermal bath. Because of a faulty experimental determination of the response times the original proposal[8] wrongly arrives at $\Delta T_{\rm lat} \gg \Delta T_{\rm el}$.

In the present paper we show that with $\Delta T_{\rm el} \gg \Delta T_{\rm lat}$ "bolometry" gives a good account of the experiments. The approach is to demonstrate, whenever possible, that the photosignal $\Delta\sigma$ can be regarded as $(\partial\sigma/\partial T)\Delta T$, or otherwise, that the identical $\Delta\sigma$ results for the same value of power absorbed by any other absorption process. Section II contains some brief notes on the experiments and Sec. III explains the bolometer model. Relevant data on the temperature-dependent conductivity of the samples are given in Sec. IV. In Sec. V we describe various experimentally observed dependences. Section VI concludes the paper with a summary and critical remarks on open ends.

The paper concerns itself with the resonant intersubband signal where the absorption stems from the surface electrons. Examples of such resonances are shown in Fig. 1. An additional, photon-frequency-independent, background signal has been observed in various reports on the photoresponse.[4,9,10] It has been identified as

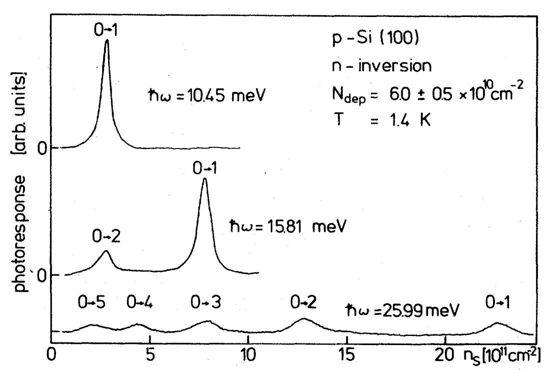

FIG. 1. Photoresponse spectra as observed in the Hitachi MOSFETs for three different frequencies.

caused by n_s-independent sample heating.[4] We have confirmed that the n_s variation of this signal gives $(\partial\sigma/\partial T)(n_s)$. The photoresponse data in Fig. 1 are characteristic of low T, where the background is negligibly small compared to the resonances. For higher T, we have subtracted the background to obtain resonance amplitudes.

II. EXPERIMENTAL NOTES

The basic apparatus and measurement procedures are described in Refs. 1 and 4. Magnetic fields up to 2.5 T can be applied. Thermal coupling between sample and He bath is by exchange gas. The sample temperature can be varied between 1.4–10 K. Laser output power is in the range 1–10 mW.

We make use of 3 Hitachi-MOSFETs[11] (metal-oxide-semiconductor field-effect transistor) with essentially identical characteristics—gate area 2×2 mm^2, oxide thickness 6300 Å, maximum mobility at 4.2 K is $\mu_{\text{eff}} = \sigma/n_s e = 14500$ cm^2/V sec for $n_s \cong 9.1\times 10^{11}$ cm^{-2}. These samples show thermally activated conduction at 1.4 K only below $n_s = 1.6\times 10^{11}$ cm^{-2}.

Measurements on the Hitachi devices were complemented with the investigation of a Bell-Labs MOSFET[12] with thermal activation behavior at 1.4 K up to $n_s \sim 9\times 10^{11}$ cm^{-2}. The other characteristics of this sample were—gate area 2.5 $\times$ 2.5 mm^2, oxide thickness 4300 Å, maximum μ_{eff} at 4.2 K is 15 000 cm^2/V sec for $n_s \cong 7.7 \times 10^{11}$ cm^{-2}.

III. BOLOMETER MODEL

The MOS device and thermal background consist of three coupled parts: surface electron gas, Si lattice, and He bath (Fig. 2). Intersubband resonance involves the absorption of power P. In a primary step the energy of perpendicular motion of a few carriers increases by $\hbar\omega$. Judging by the linewidth of the resonant absorption,[2] the lifetime of the excitation is of order 10^{-12} sec. In this time a scattering process takes place in which the excitation energy is transformed or transferred. Ando[13] has considered elastic intersubband scattering processes in which the perpendicular energy is transformed into excess kinetic energy of parallel motion. Thereafter we expect the hot electron to distribute its energy in electron-electron scattering processes. Intersubband relaxation can also take place directly via surface plasmon[14] emission, a process which would quickly and efficiently transfer the primary excitation energy to all the electrons of the subband. In either case, we believe that (for typical n_s values) the energy equilibration among electrons is faster than the competing, direct energy loss to the lattice. The photoexcited electron could in principle also dissipate its excess energy in phonon emission. Restrictions of momentum and energy, however, require a large number of successive processes to lose the photon energy.

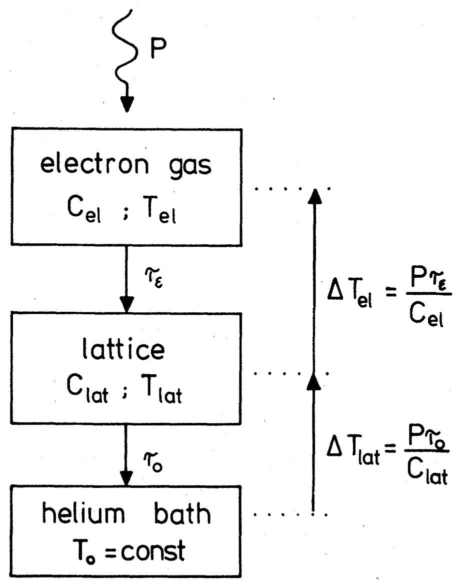

FIG. 2. Block diagram of the thermally coupled system; P is the very small power absorbed in resonant transitions between subband levels.

If, indeed, the equilibration among the electrons predominates over the direct losses to the lattice, we can consider the carrier gas as heated to a temperature ΔT_{el} above the lattice temperature. (We see additional justification of this electron temperature description in the applicability of this analysis to intersubband emission[15] and hot-electron transport experiments.[16]) The hot-electron distribution in turn will relax to the lattice temperature in the energy relaxation time τ_ϵ. We define τ_ϵ in the limit of very small ΔT_{el} as the time constant of an exponential decay which describes the relaxation of the electron gas from a Fermi distribution at $T_{\text{lat}} + \Delta T_{\text{el}}$ to the equilibrium temperature T_{lat}. The energy flow to the lattice results in a temperature rise ΔT_{lat} of the lattice relative to the bath at T_0. ΔT_{lat} depends on the thermal coupling of the sample to its surrounding. We define the relaxation time for this energy transfer as τ_0.

The time constants and temperature changes are linked in the steady state according to

$$\Delta T_{\text{el}} = \frac{P\tau_\epsilon}{C_{\text{el}}}; \quad \Delta T_{\text{lat}} = \frac{P\tau_0}{C_{\text{lat}}}, \tag{2}$$

where C_{el} and C_{lat} are the specific heats of the electrons and lattice, respectively. The relative magnitude of the two temperature changes,

$$\Delta T_{\mathrm{el}}/\Delta T_{\mathrm{lat}} = (\tau_\epsilon/\tau_0) C_{\mathrm{lat}}/C_{\mathrm{el}}\,, \tag{3}$$

depends sensitively on the thermal coupling between the various parts. An infinitesimally small heating signal $\Delta\sigma$ is the sum of two terms. We write

$$\Delta\sigma = \frac{\partial\sigma}{\partial T_{\mathrm{el}}}\Delta T_{\mathrm{el}} + \frac{\partial\sigma}{\partial T_{\mathrm{lat}}}\Delta T_{\mathrm{lat}} = \frac{\partial\sigma}{\partial T_{\mathrm{el}}}\frac{P\tau_\epsilon}{C_{\mathrm{el}}} + \frac{\partial\sigma}{\partial T_{\mathrm{lat}}}\frac{P\tau_0}{C_{\mathrm{lat}}} \tag{4}$$

and allow here for the possibility that σ may depend differently on electron and lattice temperatures.

For the case of modulation experiments, Eq. (4) gives the amplitudes as long as the frequency is small compared to the appropriate relaxation times for each of the two terms. Time-dependent solutions of the energy flow equations give τ_ϵ as the relaxation time of the first term in Eq. (4). The response of the lattice warming contribution is described by τ_0 only in the limit $\tau_0 \gg \tau_\epsilon$.

IV. SAMPLE CONDUCTIVITY

For given ΔT_{el} and ΔT_{lat} the bolometric signal depends on $\sigma(T_{\mathrm{el}}, T_{\mathrm{lat}})$. Because we wish to demonstrate the dependence of the signal on $\partial\sigma/\partial T$, we require explicit knowledge of this quantity for the samples.

In the absence of localization, σ generally decreases with rising T_{lat} or T_{el}. The measurement of the T_{lat} dependence is straightforward. To obtain $\partial\sigma/\partial T_{\mathrm{lat}}$, the change $\Delta\sigma$ for a known small ΔT_{lat} is measured. The source-drain electric field E_{SD} must be chosen sufficiently small so as not to influence the results. The T_{el} dependence can be determined indirectly by noting the influence of increasing E_{SD}, which produces a $T_{\mathrm{el}} > T_{\mathrm{lat}}$.[16] Care must be taken to avoid a simultaneous ΔT_{lat} in such a measurement. Localization implies an increasing σ when T_{lat} is raised. In this case, σ also increases with rising E_{SD} and hence T_{el}. $\Delta\sigma/\Delta T_{\mathrm{lat}}$ has been measured carefully for the Hitachi samples. The data in Fig. 3 are obtained with ΔT_{lat} of ~0.5 K and very small E_{SD}. The two n_s values are those where the $0\to 1$ transitions for $\hbar\omega = 10.45$ and 15.81 meV are observed. We note that $\Delta\sigma/\Delta T_{\mathrm{lat}}$ remains negative for all $n_s > 1.6\times 10^{11}\ \mathrm{cm}^{-2}$. It is a sensitive function of T and, as Fig. 4 shows, at fixed T, of n_s. The T dependence of these Hitachi samples is remarkable. For example, at $n_s \sim 3\times 10^{11}\ \mathrm{cm}^{-2}$ σ doubles in cooling from 4.2 to 1.4 K.

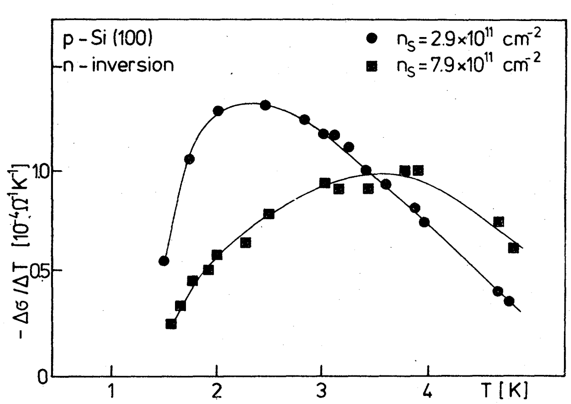

FIG. 3. $\Delta\sigma/\Delta T$ as a function of T for the Hitachi MOSFETs ($E_{\mathrm{SD}} = 0.05$ V/cm $\to T_{\mathrm{el}} \sim T_{\mathrm{lat}} = T$). The two n_s values are those where resonance transitions are observed in the experiments.

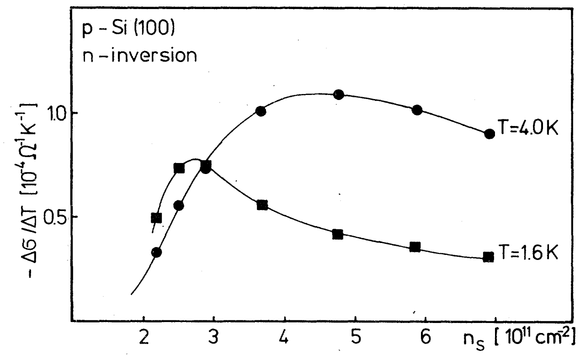

FIG. 4. $\Delta\sigma/\Delta T$ as a function of n_s for the Hitachi MOSFETs for two values of T ($E_{\mathrm{SD}} = 0.05$ V/cm $\to T_{\mathrm{el}} \sim T_{\mathrm{lat}} = T$).

In order to illuminate the nature of the T variation of σ, we have expressed the data in terms of the electron scattering rate $\Gamma = n_s e^2/\sigma m^*$. Figure 5 gives the differential scattering rate $\Delta\Gamma/\Delta T_{\mathrm{lat}}$. In published work there is reference to an approximately linear variation of $\Gamma(T)$. This phonon contribution to the scattering can be written as γT. In agreement with other authors[17] we find $\gamma \sim 3\times 10^{10}\ \mathrm{sec}^{-1}\,\mathrm{K}^{-1}$, a value which only weakly depends on n_s and applies for $T > 20$ K. For comparison we have marked this value in Fig. 5. Below 10 K, we find $\Delta\Gamma/\Delta T_{\mathrm{lat}}$ as much as one order of magnitude larger and strongly dependent on n_s. This comparison in Fig. 5 makes it unlikely that phonon scattering is the dominant mechanism. There exists no adequate theoretical description of the scattering rate at low T and low n_s as it appears in Fig. 5.

The quantity $\partial\sigma/\partial T_{\mathrm{el}}$ has not been explicitly determined for the samples, although $\sigma(E_{\mathrm{SD}})$ is known. The difficulty lies in linking a given E_{SD}

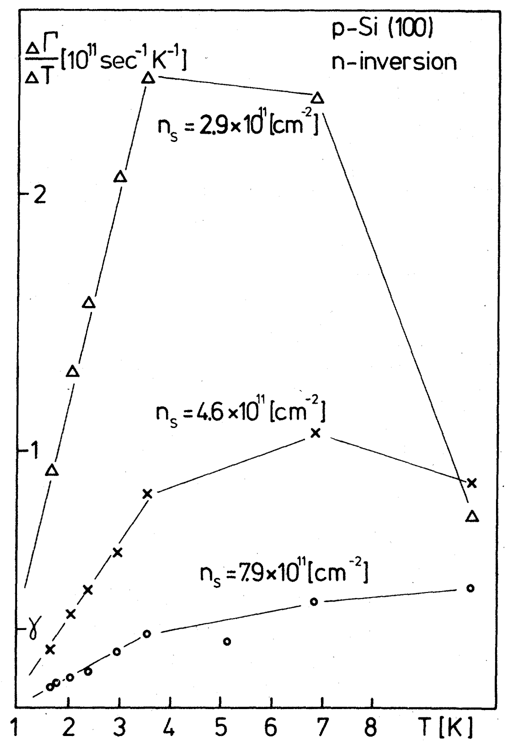

FIG. 5. Differential scattering rate $\Delta\Gamma/\Delta T$ as a function of T for several values of n_s in the Hitachi MOSFETs ($E_{SD} = 0.05$ V/cm). Above $T \sim 20$ K we find an approximately constant value $\gamma \sim 3\times10^{10}$ sec^{-1} K^{-1} for the three n_s values.

with a T_{el}. Because of our interest in the small n_s values where intersubband resonances are found, we have not found it possible to follow the procedure in Refs. 16, 18, and 19, where the Shubnikov–de Haas (SdH) oscillations are used for thermometry. The oscillations are not sufficiently well defined for low n_s. An intended, later measurement in high magnetic fields and for some of the higher n_s values was foiled by destruction of the samples.

There is reason to believe, however, that σ depends in much the same way on T_{el} and T_{lat}, so that $\partial\sigma/\partial T_{el} = \partial\sigma/\partial T_{lat} \equiv \partial\sigma/\partial T$. The latter follows if the change in phonon occupation number does not contribute much to the change in scattering. It applies if the predominant scattering is not a phonon process, as suggested by the scattering rate consideration above. It is also expected when the major change of σ stems from the change in the electron distribution function with T, even though phonon scattering dominates.

We get additional indication that the assumption $\partial\sigma/\partial T_{el} = \partial\sigma/\partial T_{lat}$ is justified from results of a series of measurements which are similar to those of Refs. 16, 18, and 19. However, instead of using the Shubnikov–de Hass amplitudes as a thermometer, we make use of the temperature-dependent σ. We measure both $\sigma(T_{lat})$ at low E_{SD} and the hot-electron conductivity $\sigma(E_{SD})$ at fixed T_{lat}. Assuming $\partial\sigma/\partial T_{lat} = \partial\sigma/\partial T_{el}$, we can now assign a T_{el} to each E_{SD} and in this way proceed to analyze the energy-loss rate in the way that it was done previously.[16,18,19] In the limit of small E_{SD}, i.e., $T_{el} \to T_{lat}$, the loss rate can be expressed as $C_{el}(T_{el} - T_{lat})/\tau_\epsilon$, with τ_ϵ equal to the time constant of a simple exponential decay. We find for $n_s = 2.9\times10^{11}$ cm^{-2} and $n_s = 7.9\times10^{11}$ cm^{-2} on our Hitachi samples a τ_ϵ of 4×10^{-8} sec at $T_{lat} = 1.4$ K. The accuracy is only within a factor of 2. From our observations we find the energy-loss rate divided by $T_{el} - T_{lat}$, i.e., the quantity C_{el}/τ_ϵ, to vary as $T_{lat}^{3.3\pm0.2}$ for temperatures between 1.4 and 4.2 K. Reference 19 arrives at an approximately T_{lat}^3 dependence. To the extent that we confirm this relation, we have thus provided evidence for the supposition $\partial\sigma/\partial T_{el} = \partial\sigma/\partial T_{lat}$.

For the Bell-Labs sample the conductivity variation with T, E_{SD}, and n_s is quite different at the densities and temperatures where the photoresponse is observed. Thermally activated conduction with positive $\partial\sigma/\partial T_{lat}$ is found up to $n_s = 9\times10^{11}$ cm^{-2} at 1.4 K and low E_{SD}. In order to discuss the photosignal in these samples, we have obtained a sequence of curves for $\sigma(T)$ with $1.4\text{K} \leq T_{lat} \leq 4.2$ K and fixed E_{SD} values between 0.01 and 0.5 V/cm. With increasing E_{SD}, $\Delta\sigma/\Delta T_{lat}$ decreases and finally reverses in sign (fixed T_{lat}). At these high E_{SD} values localization is removed. $\Delta\sigma/\Delta T_{lat}$ is negative and has a magnitude comparable to that for the Hitachi samples. We know from these data also the variation of σ with increasing E_{SD} at fixed T. At first, σ increases with rising E_{SD}. For high E_{SD}, $\Delta\sigma/\Delta E_{SD}$ becomes negative as in the metallic regime.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The bolometry concept is based on the idea that absorption of energy leads to a temperature change ΔT and that the resultant signal $\Delta\sigma = (\partial\sigma/\partial T)\Delta T$. The experiments have been devised in order to test a relationship of this form. In particular the role that $\partial\sigma/\partial T$ plays has been examined. As an alternative and even more direct approach to bolometry we have aimed to demonstrate that a given $\Delta\sigma$ results for a given power flow to the electron gas independent of the absorption mechanism.

We discuss the various different investigations in Secs. V A–V F below.

A. Response times: Hot-electron versus hot-sample bolometry

The resonant photoresponse, under the usual conditions of the experiment, is a fast signal. The slow, msec-type of response times cited in early reports has not been substantiated.[1,4] There is now general agreement that the response is faster than 10^{-5} sec. It cannot be properly measured using mechanical chopping of the laser beam.

A second observation that we have made is that the resonance signal amplitude is independent of the sample-to-bath thermal coupling. The latter can be varied considerably with the exchange-gas pressure. Evidence for a change of this coupling comes from the background signal, whose amplitude and response time τ_0 depend on the gas pressure. Both the fast response and lack of dependence on τ_0 point to the ΔT_{el} term in Eq. (4) for the resonance signal.

The fact that one observes at low T ($T < 4.2$ K) predominantly a hot-electron effect follows from a comparison of ΔT_{el} and ΔT_{lat} as in Eq. (3). At $T \simeq 1.4$ K the ratio of specific heats is calculated as $C_{lat}/C_{el} \simeq 1 \times 10^5$. The time τ_ϵ has been obtained (cf. Sec. IV) as 4×10^{-8} sec at this temperature.

The time τ_0 can in principle be obtained from the modulation frequency variation of the background signal amplitude. At 4.2 K this time for the usual experimental conditions in our apparatus is 10^{-3} sec. When cooled to 1.4 K, the background signal becomes so fast ($\tau_0 \leq 10^{-5}$ sec) that it cannot properly be measured with mechanical beam chopping. Putting the various numbers together, it follows that $\Delta T_{el}/\Delta T_{lat} \geq 400$ at 1.4 K.

At higher values of T this ratio of temperature changes becomes smaller. While $C_{lat}\tau_\epsilon/C_{el}$ is largely T independent (cf. Sec. IV), the measured τ_0 is at least 100 times larger at 4.2 K. It is possible, particularly if the thermal coupling to the bath is poor, that the resonance becomes a hot-sample signal above 4.2 K.

B. Sign of the photoresponse: The localization problem

In a bolometric formulation of the photoresponse the sign of the signal is unambiguously linked to the sign of $\partial\sigma/\partial T$. The ΔT_{el} caused by absorption of radiation is positive. It follows that photosignal and $\partial\sigma/\partial T$ must have the same sign. For the Hitachi samples both are always negative where resonances can be observed. The requirement is evidently satisfied.

The Bell-Labs sample allows a more explicit test. In this sample activated conductivity ($\partial\sigma/\partial T$ positive) is found at n_s and T values where we observe resonances in the photoresponse. Under these conditions $\partial\sigma/\partial T$ is a sensitive function of E_{SD} and T. With increasing E_{SD} or T, localization can be lifted and $\partial\sigma/\partial T$ will switch sign. Only the E_{SD} dependence can be satisfactorily examined. A test of the T dependence, which must be done at very low E_{SD}, has not been possible, because the sign reversal occurs at such high T that the photosignal cannot any longer be adequately observed (cf. Sec. V D).

A superficial check on the sign with very small (5 mV/cm) and very large (0.5 V/cm) E_{SD} seemingly gives the expected result. The resonance at $n_s \simeq 6.0 \times 10^{11}$ cm^{-2} ($\hbar\omega = 15.81$ meV) gives a positive $\Delta\sigma$ for small E_{SD} ($\partial\sigma/\partial T$ positive). The $0 \rightarrow 1$ transition for $\hbar\omega = 10.45$ meV falls at such low n_s that it is not observed at all. Both σ and $\partial\sigma/\partial T$ are vanishingly small there. With large E_{SD} both resonances are observed with negative sign, in accord with the lifting of localization at this E_{SD}. We have measured a sequence of photoresponse curves for successively higher E_{SD} that so closely resemble those in Fig. 6 of Ref. 5 that there is no need to reproduce our results here. This detailed examination of the E_{SD} dependence reveals a disconcerting fact. The resonance in the photoresponse does not correlate well in sign and magnitude with the $\Delta\sigma/\Delta T_{lat}$ obtained from the conductivity curves mentioned earlier in Sec. IV.

For high E_{SD} the comparison with $\Delta\sigma/\Delta T_{lat}$ is not justified. One reason is that the procedure for obtaining $\Delta\sigma/\Delta T_{lat}$, i.e., measuring $\Delta\sigma$ for a small ΔT_{lat}, gives $\partial\sigma/\partial T$ only for very small E_{SD}. High E_{SD} heats the electron gas to a T_{el} above T_{lat}. A positive ΔT_{lat} now results in a simultaneous reduction of $T_{el} - T_{lat}$ because the energy loss of the electron gas is faster at higher T_{lat}, while the power input remains approximately constant. Thus $\Delta\sigma/\Delta T_{lat}$ is not $\partial\sigma/\partial T$, because the temperature change leading to $\Delta\sigma$ is not only ΔT_{lat}. There is an additional, unknown ΔT_{el} change.

Instead of using $\partial\sigma/\partial T$ explicitly, we formulate the bolometry concept in terms that lead us to another, more direct experimental evaluation procedure. We require that any given small amount of power absorbed by the electrons, *regardless of the specific excitation mechanism*, leads to the same effect on the conductivity. Thus if $\Delta\sigma$ is a bolometric signal, it has to behave like the σ change induced by a small increase of source-drain current heating. From the variation of σ with E_{SD}, we construct the dependence of σ on the source-drain power dissipation P_{SD} at fixed T_{lat}. Here $P_{SD} = A\sigma E_{SD}^2$, with A equal to the gate area. By graphical differentiation we obtain $(\Delta\sigma/\Delta P_{SD})(E_{SD})$ and compare it with the photoresponse $\Delta\sigma$ at the same E_{SD}. $\Delta\sigma/\Delta P_{SD}$ is the expected sensitivity of σ for small changes of the thermal energy of the electron gas.

In the localization regime, even a rough comparison along these lines makes the problem evident. The two quantities do not relate well. In particular, the point where $\Delta\sigma/\Delta P_{SD}$ turns from positive to negative occurs at an E_{SD} where the photosignal has already switched sign and has a considerable amplitude. The implication is immediate. The additional power into the electron system by resonant absorption of photons gives a signal $\Delta\sigma$, whereas under identical conditions additional source-drain power gives zero signal. This observation is an obvious violation of the bolometry concept.

The "localization problem" has in essence been shown up independently by other groups.[20,21] The fact that it is found in several different samples argues that it is not simply an experimental artifact produced for example by an added non-Ohmic resistance at the source-drain contacts. This would have provided a possible explanation for the problem. Another reason may be a failure to achieve thermal equilibrium of the absorbed energies. The possibility that the response in the localized state may depend on the specific energy absorption process cannot be precluded. We believe that the difficulty which we encounter here is more of a commentary on the as-yet-unresolved specifics of localization than a general failure of the bolometry concept. All following results apply to conditions when localization is lifted.

C. Signal amplitude: E_{SD} dependence

The photosignals are strongest at lowest T and small E_{SD}. For the present experiments we can obtain maximum relative conductivity changes $\Delta\sigma/\sigma$ of order 10^{-3}. The exact value depends on n_s at resonance and naturally on the absorption associated with a specific transition. The signal amplitude varies linearly with laser power.

To verify that effects of this magnitude can be caused by electron heating, we again compare with the effect of source-drain Ohmic losses on σ. For the Hitachi samples the $\sigma(P_{SD})$ data at $T=1.4$ K are shown for two values of n_s as insets in Fig. 6. The result of the graphical differentiation, the quantity $\Delta\sigma/\Delta P_{SD}$, is plotted in the same figure below. For a given resonance transition the power input can be estimated. We measure the laser output power and take into account losses in the light pipes, losses due to focusing on the sample, and dielectric reflection losses at the sample surface. Together with the measured fractional absorption (typically 0.5–3 $\times 10^{-4}$) we arrive at a figure for the power ab-

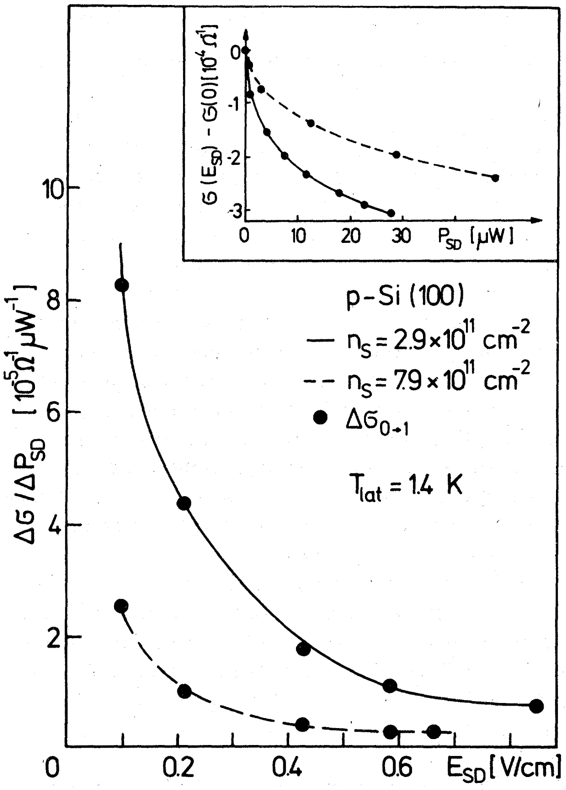

FIG. 6. $\Delta\sigma/\Delta P_{SD}$, the derivative of σ with respect to the source-drain power dissipation, as a function of the source-drain field E_{SD}. ($P_{SD} = A\sigma E_{SD}^2$—$A$ is the gate area.) The dots are the photoresponse amplitudes (arbitrary units) at various E_{SD}. They have been fitted at $E_{SD} \sim 0.6$ V/cm. The inset gives the change in σ vs P_{SD} and has been used to construct $\Delta\sigma/\Delta P_{SD}$.

sorbed at resonance. The product of this power with $\Delta\sigma/\Delta P_{SD}(n_s)$ at a certain E_{SD} estimates the strength of a resonance heating signal. The result agrees satisfactorily with $\Delta\sigma$ measured at this same E_{SD} and n_s.

Such an estimate has of course a considerable uncertainty, because some of the quantities entering are only known with poor accuracy. An additional test of the relation $\Delta\sigma_{0\to1} \propto \Delta\sigma/\Delta P_{SD}$ is provided by measuring the photoresponse amplitude as a function of E_{SD} (the latter does not change the subband absorption). We have done so for the $0\to1$ transitions at $n_s = 2.9\times10^{11}$ cm^{-2} and $n_s = 7.9\times10^{11}$ cm^{-2}. The results are entered as solid points on the curves in Fig. 6. In each case a single point has been fitted to the line. We find very convincing agreement of the photosignal with the $\Delta\sigma/\Delta P_{SD}$ curve over as much as a factor of 20 in magnitude.

D. T_{lat} dependence

Intersubband resonance absorption has been observed up to 130 K.[22] Good photoresponse signals are resolved only below about 10 K. Their amplitudes increase by more than two orders of magnitude, when T_{lat} is reduced to 1.4 K. Figures 7 and 8 show the photoresponse amplitude $\Delta\sigma_{0\to 1}$ vs $1/T_{lat}$ at two E_{SD} values for the $0\to 1$ resonances at $\hbar\omega = 10.45$ meV and $\hbar\omega = 15.81$ meV for Hitachi samples.

For lowest E_{SD} the T_{lat} dependence of $\Delta\sigma_{0\to 1}$ is roughly a power law $T_{lat}^{-\alpha}$ over at least two decades in amplitude. The exponent α is different for the two cases (Figs. 7 and 8). The amplitude of the $0\to 2$ transition signal for $\hbar\omega = 15.81$ meV could be obtained reliably only below ~2.6 K. In the limited range 1.4 K $\leq T_{lat} \leq$ 2.6 K, the amplitude of the $0\to 2$ signal increases by one order of magnitude. The T_{lat} dependence is that of the $0\to 1$ signal for $\hbar\omega = 10.45$ meV, which for the particular depletion charge of the Hitachi samples occurs at about the same n_s. This suggests that the final state of the subband transition and the excitation energy $\hbar\omega$ have no influence, and that n_s is the relevant parameter which determines the strength of the T_{lat} dependence.

When E_{SD} is very small, we expect T_{el} and T_{lat} to equal a common value T. The electronic bolometer signal term in Eq. (4) contains the factor τ_ϵ/C_{el}. The measured T dependence of this quantity is $T^{-3.3}$, essentially independent of n_s (cf. Sec. IV). Different T dependences of signals come about because of the function $\partial\sigma/\partial T(T)$ which depends on n_s (Fig. 3). To demonstrate explicitly this expected relationship we have constructed in Fig. 9 the quantity $\Delta\sigma_{0\to 1}/(\Delta\sigma/\Delta T)$ vs T for the two $0\to 1$ signals in Figs. 7 and 8 (E_{SD} low). The curves have been adjusted to coincide at 4.2 K. Whereas the $\Delta\sigma_{0\to 1}$ at different n_s values have different T dependences, $\Delta\sigma_{0\to 1}/(\Delta\sigma/\Delta T)$ vary identically with T over about a factor of 50 in magnitude. Thus $\Delta\sigma/\Delta T(T)$ really is the reason for the difference. The exponent -3.3 provides a reasonable description of the T-variation of $\Delta\sigma_{0\to 1}/(\Delta\sigma/\Delta T)$.

$\Delta\sigma_{0\to 1}$ at high E_{SD} (0.6 V/cm) in Figs. 7 and 8 deviates more from the low-field value the lower T_{lat} is. The T_{lat} variation of the high E_{SD} signals

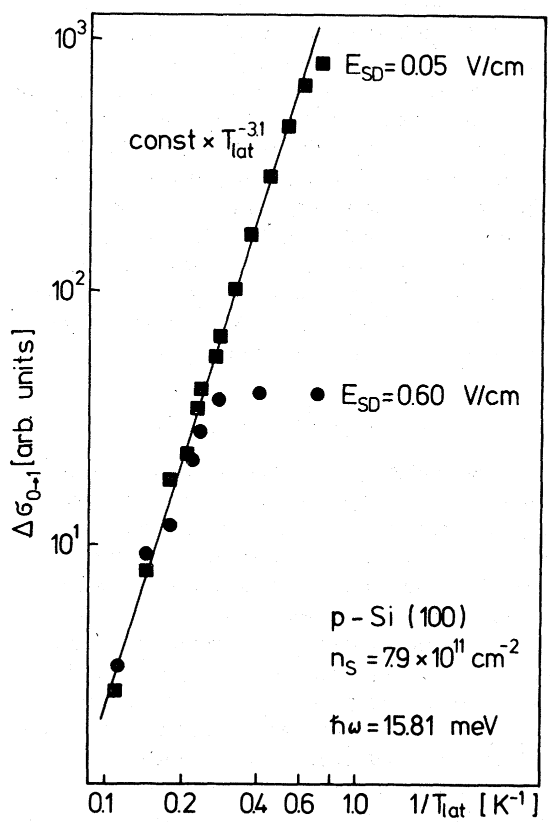

FIG. 7. Amplitude of the photosignal $\Delta\sigma_{0\to 1}$ vs $1/T_{lat}$ for two different E_{SD}.

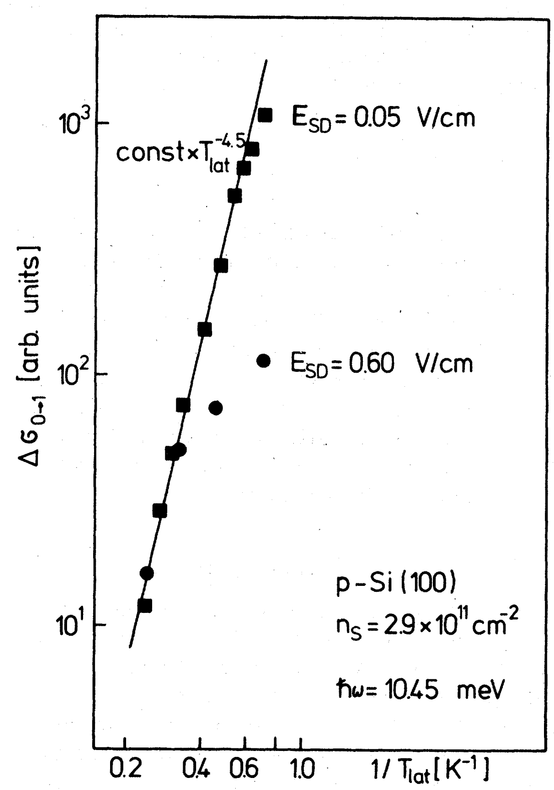

FIG. 8. Amplitude of the photosignal $\Delta\sigma_{0\to 1}$ for $\hbar\omega$ =15.81 meV vs $1/T_{lat}$ for two different E_{SD}.

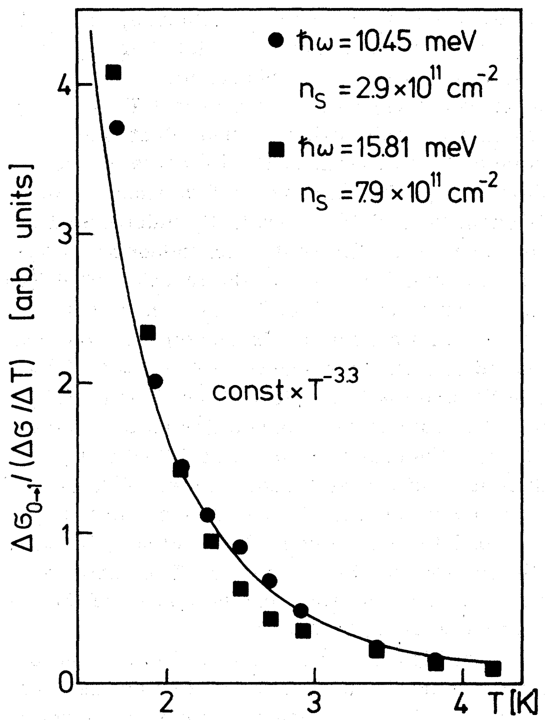

FIG. 9. Photosignal $\Delta\sigma_{0\to1}$ divided by $\Delta\sigma/\Delta T$ vs T for $n_s = 2.9\times10^{11}$ cm^{-2} and $n_s = 7.9\times10^{11}$ cm^{-2} (both with $E_{SD} = 0.05$ V/cm$\to T_{el} \sim T_{lat} = T$). These normalized signals have the same T dependence, approximately the $T^{-3.3}$ relation expected for the thermal resistance of the electrons to the lattice, i.e., the quantity τ_ϵ/C_{el} The various quantities have been fitted to the point at 2.1 K.

is relatively weak. As has been shown in Sec. V C, the reduction of signal amplitudes at high E_{SD} over the low-field value is exactly that expected for a heating effect. The reason for the smaller amplitude is that P_{SD} creates a $T_{el} > T_{lat}$. The effect is stronger the lower T_{lat} is, because with decreasing temperature the thermal coupling of the electrons to the lattice is reduced. Above ~4 K with $E_{SD} = 0.6$ V/cm the electron heating effect is apparently negligible.

E. n_s dependence of the signal amplitude

When the subband resonance spectrum contains the higher-order transitions $0\to2$, $0\to3,\ldots$ in addition to $0\to1$, we find the relative amplitudes in the photoresponse spectrum to differ from the respective amplitudes in the absorption spectrum. How they differ depends on the temperature at which we make the comparison.

From Eq. (4) such a difference could arise for two reasons. For one, the ΔT_{el} for a given power absorption and at fixed T_{lat} depends on the thermal coupling of electrons to the lattice (the factor τ_ϵ/C_{el}). This factor possibly contains a weak n_s dependence. Second, and most important, the term $\partial\sigma/\partial T$ varies considerably with n_s (compare Fig. 4). In a comparison of the photoresponse amplitudes with an absorption spectrum, both of these factors need to be considered. This can be done most conveniently in terms of the quantity $\Delta\sigma/\Delta P_{SD}$, which contains the combination of the two effects considered above. We discuss below some spectra on the Hitachi samples in these terms.

For $\hbar\omega = 10.45$ meV the $0\to2$ transition falls at $n_s \sim 0.5\times10^{11}$ cm^{-2}, where $\Delta\sigma/\Delta P_{SD}$ is essentially zero. The $0\to2$ resonance is not seen in the photoresponse curve at 1.4 K, even though it appears in the absorption spectrum. This provides qualitative confirmation of the expected n_s dependence.

With $\hbar\omega = 15.81$ meV both the $0\to1$ and $0\to2$ peaks are seen in absorption and in the photoresponse. The ratio of power absorption $P_{0\to1}/P_{0\to2}$ is ~13. For $E_{SD} = 0.1$ V/cm and $T = 1.4$ K, the quantity $\Delta\sigma/\Delta P_{SD}$ at the n_s value of the $0\to2$ resonance is 3.5 times bigger than for the n_s of the $0\to1$ transition. We form $P\cdot\Delta\sigma/\Delta P_{SD}$ for the two resonances and predict the amplitude ratio of the two transitions in the photoresponse as 3.7. The experimental ratio $\Delta\sigma_{0\to1}/\Delta\sigma_{0\to2}$ is close to 4. It is possible to repeat this check at different values of T_{lat}. We find always a satisfactory description of this amplitude ratio.

Figure 1 is another example which shows qualitatively the correct behavior. The small amplitude of the $0\to1$ resonance at $\hbar\omega = 25.99$ meV is related to the small value of $\Delta\sigma/\Delta P_{SD}$ at the high n_s of 2.3×10^{12} cm^{-2}. The absorption spectrum gives $0\to1$ as the biggest signal.

F. Photoresponse in a magnetic field

The application of a magnetic field B, perpendicular to the sample surface, allows a particularly interesting demonstration of the bolometric character of the photoresponse. In previous work[23] it has been shown that the intersubband absorption is independent of B. It follows from Eq. (4) that the resonant photoresponse signal must have the B dependence of $(\tau_\epsilon/C_{el})(\partial\sigma/\partial T)$.

In the experiments we hold n_s constant at the value for the $0\to1$ resonance and sweep the field B. The signal $\Delta\sigma_{0\to1}$ is shown in Fig. 10. It shows a rapid decrease, followed by SdH oscillations above ~1 T. For certain limited ranges of B values there is even a sign reversal. For these values of B, $\Delta\sigma_{0\to1}$ is actually positive,

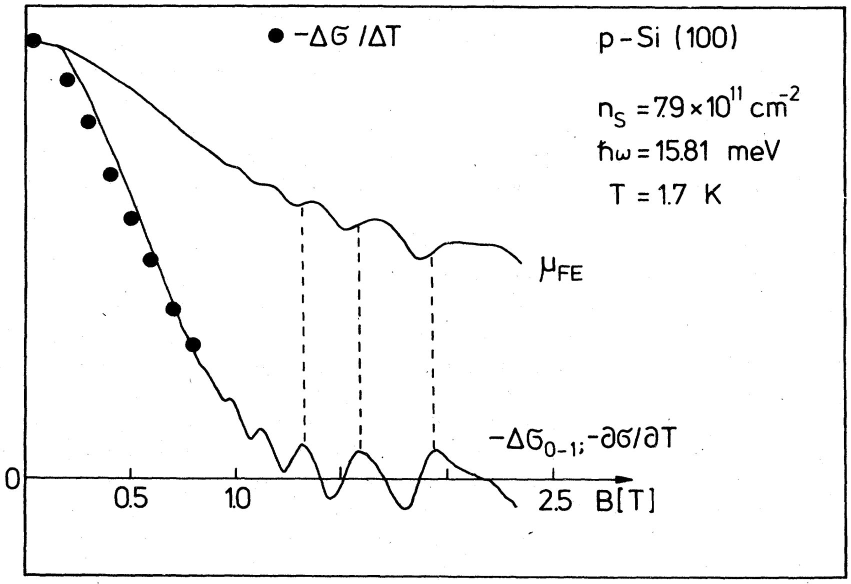

FIG. 10. Comparison of the magnetic field dependence of the photosignal $\Delta\sigma_{0\to1}$, $\partial\sigma/\partial T$ (from the background), μ_{FE} (i.e., $\partial\sigma/\partial V_g$) and $-\Delta\sigma/\Delta T$ (solid dots) obtained from a differential conductivity measurement.

whereas at $B = 0$ it is negative.

For comparison we also show in Fig. 10 the variation of the field-effect mobility μ_{FE} with B, under the same conditions. We match up the curves at $B = 0$ and find that the two do not relate at all. There is an approximate 90° phase shift in the oscillatory component of the two curves: μ_{FE} never turns negative in the available field range and decreases much more slowly at low B. We comment on this later in Sec. VI.

We have measured also $\sigma(B)$ directly at temperatures T and $T + \Delta T$, with $\Delta T \sim 0.3$ K about $T = 1.7$ K. The differences $\Delta\sigma$ are entered as solid points after matching up at $B = 0$. Over the range 0–0.7 T, where these differences can be determined with good precision, we find an excellent fit to the photosignal.

With increasing B, σ itself and the differences $\Delta\sigma$ become quite small. We cannot conveniently follow the above procedure. For this reason we make use of the so-called background signal,[3,4,9] which is known to represent the effect of thermal modulation of the entire sample, and therefore is a measure of $\partial\sigma/\partial T(B)$. By removing most of the exchange gas we make this signal sufficiently big and observe it with a lower frequency $\hbar\omega$ (compare Ref. 9), but at the same n_s at which previously the $\Delta\sigma_{0\to1}$ had been obtained. After fitting at $B = 0$, we obtain a curve which in every respect matches the $\Delta\sigma_{0\to1}$ signal. Therefore we have labeled in Fig. 10 the curve with both $\Delta\sigma_{0\to1}$ and $\partial\sigma/\partial T$.

The observations allow us to conclude that in these Hitachi samples the field dependence of the photosignal is unambiguously that of $\partial\sigma/\partial T$. The quantity τ_ϵ/C_{el}, the thermal resistance of the electrons to the lattice, apparently does not vary much with B.

VI. CONCLUDING REMARKS

With the experimental results of Sec. V, we have demonstrated that, at least for the case of non-activated metallic conduction, subband resonance observed in the dc conductivity is a hot-electron-bolometric effect. The observations and this conclusion apply to both the Hitachi and Bell-Labs sample, the latter when it is examined under experimental conditions for which localization is removed.

In many different ways we have sought to bring out the proportionality of the photoresponse to the function $\partial\sigma/\partial T$. The most clear-cut demonstration of this is the magnetic field experiment (Sec. V F), but also the T dependence and n_s dependence of the signal amplitude (Secs. V D and V E) point to $\partial\sigma/\partial T$ as the relevant parameter.

The second approach has been to demonstrate the relation of the photosignal to the well-known heating effect of the source-drain power. In this way, we have made intelligible the observed signal amplitude and the E_{SD} dependence (Secs. V B and V C). This equivalence of effects caused by completely different excitation mechanisms, once a dc electric field parallel to the sample surface, once infrared radiation polarized perpendicular to the surface, is an essential feature of the bolometric idea. The relevant quantities are the energy absorbed and the resultant heating of the electron gas. The signal $\Delta\sigma$ registers only the temperature change induced by the absorption. A logical consequence is the prediction that hf Drude absorption or cyclotron resonance must also be observable as photoresponse with equal $\Delta\sigma$ for equal power absorbed. The thick Al gates of the present samples have prevented us from providing a demonstration of these effects. In InSb, Därr *et al.*[24] have observed cyclotron resonance photoresponse and have shown the bolometric character of the signal.

In case of localization, as in the Bell-Labs sample, there are difficulties in applying the bolometer concept. We have failed to find the postulated simple relation of the photosignal and E_{SD} heating. If one tries to explain the positive photoresponse under localized condition in terms of photoexcitation of bound carriers into high-energy, conducting states, one also encounters difficulties. One then expects a $0\to 1$ transition signal with 10.45 meV at $n_s = 2\times 10^{11}$ cm^{-2} in the Bell-Labs sample, when localization is strong (E_{SD} very small) and both σ and $\partial\sigma/\partial T$ are vanishingly small, because $\hbar\omega$ is bigger than the activation energy at this n_s.[25] Although this transition is readily observed in absorption, there is no photosignal (cf. Sec. V B).

The experimental results not only plead for a bolometric explanation, but also disprove the alternative, photoconductivity-type of explanation mentioned in Sec. I. The postulated proportionality $\Delta\sigma \propto \mu_{FE}$ in Ref. 1 is convincingly refuted by the magnetic field dependence (Sec. V F). The positive signals in the localization regime or in certain magnetic field ranges disprove any model with photoexcitation into trap states. It is also difficult to imagine a model based on an intermediate trap[7] or subband[6] level which has the observed T dependence.

The electronic bolometer description gives good account of most observations. It is simple and provides definitive predictions. Nevertheless, we must keep in mind that some basic assumptions have entered in the course of our arguments. We have no independent proof of the postulated fast energy equilibration among the electrons, or for the hypothesis $\partial\sigma/\partial T_{el} \simeq \partial\sigma/\partial T_{lat}$. The experiments mostly show that various dependences for the relative signal amplitude are satisfied. As for the absolute signal amplitude we have only the estimate in Sec. V C.

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[1] R. G. Wheeler and H. S. Goldberg, IEEE Trans. Electron. Devices 22, 1001 (1976).
[2] P. Kneschaurek, A. Kamgar, and J. F. Koch, Phys. Rev. B 14, 1610 (1976).
[3] A. Kamgar, D. C. Tsui, and M. D. Sturge, Solid State Commun. 24, 47 (1977).
[4] F. Neppl, J. P. Kotthaus, J. F. Koch, and Y. Shiraki, Phys. Rev. B 16, 1519 (1977).
[5] C. C. Hu, J. Pearse, K. M. Cham, and R. G. Wheeler, Surf. Sci. 73, 207 (1978).
[6] G. H. Döhler, Solid State Commun. 18, 633 (1976).
[7] R. G. Wheeler (private communication).
[8] F. Neppl, J. P. Kotthaus, J. F. Koch, Y. Shiraki, and G. Dorda, presented at the International Conference on the Electronic Properties of Two-Dimensional Systems, Berchtesgaden, 1977 (unpublished).
[9] Y. Shiraki, J. Phys. C 10, 4539 (1977).
[10] A. Kamgar, M. D. Sturge, and D. C. Tsui, Surf. Sci. 73, 166 (1978).
[11] Samples provided by N. Kotera and Y. Katayama, Hitachi Laboratories.
[12] Samples provided by D. C. Tsui and E. Gornik, Bell Laboratories.
[13] T. Ando, Z. Phys. B 24, 33 (1976).
[14] S. J. Allen, Jr., D. C. Tsui, and R. A. Logan, Phys. Rev. Lett. 38, 980 (1977); T. N. Theis, J. P. Kotthaus, and P. J. Stiles, Solid State Commun. 24, 273 (1977).
[15] E. Gornik and D. C. Tsui, Phys. Rev. Lett. 37, 1425 (1976).
[16] K. Hess, Lecture Notes, International Conference on the Application of High Magnetic Fields in Semiconductor Physics, Würzburg, p. 90 (1976).
[17] See, e.g., H. Küblbeck and J. P. Kotthaus, Phys. Rev. Lett. 35, 1019 (1975).

[18]K. Hess, T. Englert, T. Neugebauer, G. Landwehr, and G. Dorda, Phys. Rev. B 16, 3652 (1977).
[19]T. Neugebauer and G. Landwehr, Verhandlungen der DPG, Freudenstadt, 1978, p. 57 (unpublished).
[20]R. G. Wheeler (private communication).
[21]J. Allen, Jr. (private communication).
[22]P. Kneschaurek and J. F. Koch, Phys. Rev. B 16, 1590 (1977).
[23]W. Beinvogl and J. F. Koch, Phys. Rev. Lett. 40, 1736 (1978). W. Beinvogl, Ph.D. thesis (TU München, 1977) (unpublished).
[24]A. Därr, A. Huber, and J. P. Kotthaus, *Proceedings of the Third International Conference on the Physics of Narrow-Gap Semiconductors* (PWN Polish-Scientific Publ., Warsaw, 1978), p. 417; A. Därr, Ph.D. thesis (TU München, 1978) (unpublished).
[25]S. J. Allen, Jr., D. C. Tsui, and T. De Rosa, Phys. Rev. Lett. 35, 1359 (1975).