Nonlinear far-infrared absorption in InSb due to light impact ionization

S. D. Ganichev,[a] J. Diener, and W. Prettl
Institut für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany

(Received 29 November 1993; accepted for publication 8 February 1994)

A highly nonlinear far-infrared free-carrier absorption, rising with the radiation intensity, has been observed in InSb. It is shown that the nonlinearity arises from an increase in the number of free carriers caused by the generation of electron-hole pairs by light impact ionization in the radiation field of a powerful far-infrared laser. The observed nonlinearity permits the investigation of the process of impact ionization by a contactless optical method.

We report on the first experimental observation of the nonlinear increase in free-carrier absorption in semiconductors with rising far-infrared radiation intensity. Samples of InSb were investigated at photon energies, $\hbar\omega$, much less than the gap energy, E_g. It is shown that the nonlinearity arises from an increase in the number of free carriers, caused by light impact ionization in the radiation field of a far-infrared laser. The phenomena of avalanche multiplication of the photocurrent and impact ionization in $A^{\mathrm{III}}B^{\mathrm{V}}$ semiconductor compounds and in their solid solutions are currently attracting considerable attention. This is not simply due to the wish to study the behavior of hot carriers and the characteristic features of impact ionization processes in such semiconductors. Rather, the impact ionization process is of great practical importance for high efficiency solar cells[1] and in photodetectors with internal amplification like avalanche photodiodes, particularly useful in the case of fiber-optic communication systems.[2] Additionally the autocatalytic nature of impact ionization leads to impurity breakdown and the formation of dynamic structures in high purity materials.[3,4]

Impact ionization of semiconductors has been extensively studied by applying static and low frequency electric fields,[5–8] when the frequency of the electric field oscillation is less than the reciprocal relaxation time of free carriers ($\omega\tau \ll 1$) and ionization is due to the acceleration of electrons in one-half period. Recently, impact ionization has also been observed in the high frequency electric field of an optical wave in the opposite limit $\omega\tau \gg 1$.[9] In this case, carriers acquire high energies entirely because of collisions in the presence of a high-frequency electric field and an increase in τ reduces the heating effect. The present observation of nonlinear far-infrared absorption of carriers, generated by light impact ionization, represents an optical method to study the charge multiplication at high electric fields in semiconductors and the properties of hot carriers.

The transmission of far-infrared radiation through InSb slices as function of the radiation intensity has been investigated. The measurements were carried out on n-type and p-type InSb with carrier densities in the range from 10^{13} cm^{-3} to 5×10^{15} cm^{-3}. The samples were placed in an optical cryostat and were cooled by liquid nitrogen. The intensity of incident and transmitted radiation was measured by fast (time resolution better than 0.5 ns) far-infrared photon drag and intraband photoconductivity detectors made of n-type Ge(ARTAS models PD-5F and IPA-2F, respectively). The response of the detectors was linear throughout the investigated range of intensities. The radiation sources used were pulsed far-infrared NH_3 and CH_3F molecular lasers optically pumped by a TEA CO_2 laser providing 40 ns pulses. The measurements were carried out at the wavelengths $\lambda=90.5$, 152, and 250 μm. The corresponding photon energies of 13.7, 8.2, and 5 meV, respectively, are much smaller than the energy gap of InSb, $E_g=224$ meV at $T=77$ K. The maximum intensity of radiation in the sample was 3 MW/cm^2. For varying the intensity calibrated teflon attenuators were utilized. A series of cold and warm black polyethylene (~1 mm thick), teflon, and crystal quartz windows were used to transmit far-infrared radiation while rejecting near-infrared and visible light.

It has been observed that an increase in intensity incident on the InSb samples at $T=77$ K resulted in an increasing of the radiation absorption in the samples. The reciprocal transmission $\Lambda^{-1}=I_{\mathrm{in}}/I_{\mathrm{out}}$, rose by about a factor of 5 at the highest available intensity. I_{in} and I_{out} are the intensities of light entering and leaving the crystal, respectively. In addition, the presence of a nonlinear absorption could also have been deduced from an increase of the duration of the radiation pulse transmitted through the sample at high intensities. This observation rules out other mechanisms, such as scattering. Nonlinear absorption has been observed with all p- and n-type samples and for all carrier densities. The thickness of the samples d were chosen to satisfy the condition $K_0d>1$, where K_0 is the absorption coefficient in the limit of low light intensity. Thus, the absorption is strong enough so that interference effects can be neglected. Figures 1 and 2 show the dependence of Λ^{-1} on I_{in} obtained in $n-$InSb with $n=1\times10^{13}$ cm^{-1} and 3.8×10^{15} cm^{-3} measured at a wavelength $\lambda=90.5$ μm. It is seen that the Λ^{-1} rises with increasing I_{in} and the slope of the curves changes with the thickness d (Fig. 1). The intensity of radiation at which Λ^{-1} starts to increase is found to be of the same order of magnitude for different dark carrier densities but it is different for different wavelengths. Increasing of the wavelength leads to an onset of the nonlinearity at a substantially lower level of intensity. This is seen in Fig. 2, which shows results obtained on one sample for two different wavelengths, 90.5 and 250 μm. Measurements carried out on p-type InSb (Fig. 3) basically

---

[a] Alexander von Humboldt Fellow, Permanent address: A. F. Ioffe Physicotechnical Institute, Russian Academy of the Sciences, St. Petersburg 194021, Russia.

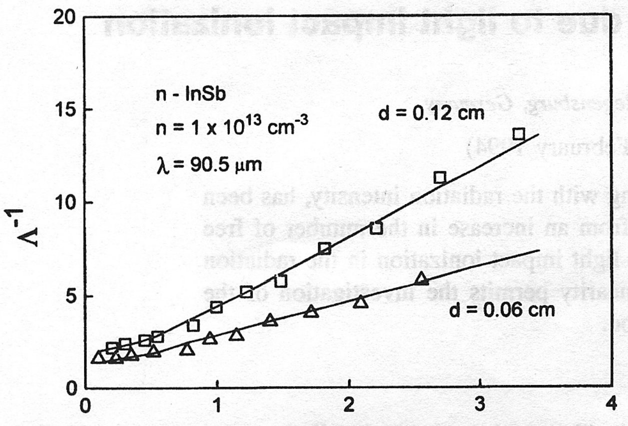

FIG. 1. Reciprocal transmission $\Lambda^{-1}=I_{in}/I_{out}$ as a function of the incident radiation intensity $I_{in}(\lambda=90.5\ \mu m)$ for $n-$InSb at $T=77$ K with $n=10^{13}$ cm^{-3} of thickness $d=0.12$ cm (squares), 0.06 cm (triangles). Solid lines are calculations following Eqs. (1)–(4) with $E_c=1.3\times10^4$ V/cm.

gave the same results. Recently, the generation of electron-hole pairs in InSb by far-infrared radiation has been observed, in spite of the fact that the photon energy was several factors of ten less than the energy gap.[9] The experimental results and theoretical considerations revealed that the generation mechanism is light impact ionization. Generation of free carriers at liquid nitrogen temperature was observed in the same intensity range, and showed an identical wavelength dependence as the presently studied onset of nonlinear absorption. Furthermore, the impact ionization probability was almost independent of the dark carrier density, like the absorption observed here. These similarities lead us to describe the effect by free carrier absorption by assuming that the density of carriers rises with increasing radiation intensity as a result of electron-hole pairs generation caused by strong free carrier heating in the high electric field of the far-infrared radiation.

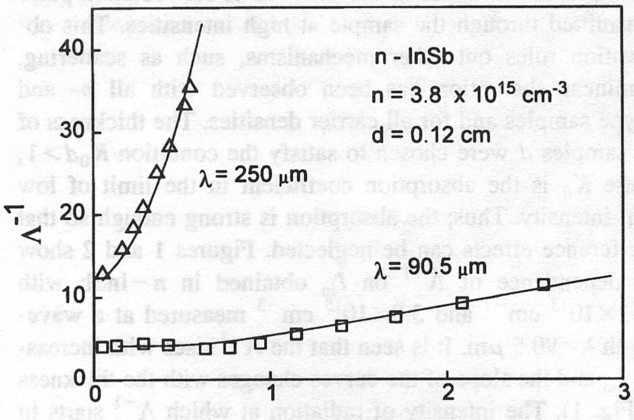

FIG. 2. Reciprocal transmission $\Lambda^{-1}=I_{in}/I_{out}$ for $n-$InSb ($T=77$ K, $n=3.8\times10^{15}$ cm^{-3}, $d=0.12$ cm) as a function of the incident intensity I_{in} of wavelengths: 90.5 μm (squares), 250 μm (triangles). Solid lines are calculations following Eqs. (1)–(4) with parameters $E_c=2.2\times10^4$ V/cm ($\lambda=90.5$ μm) and $E_c=0.6\times10^4$ V/cm ($\lambda=250$ μm).

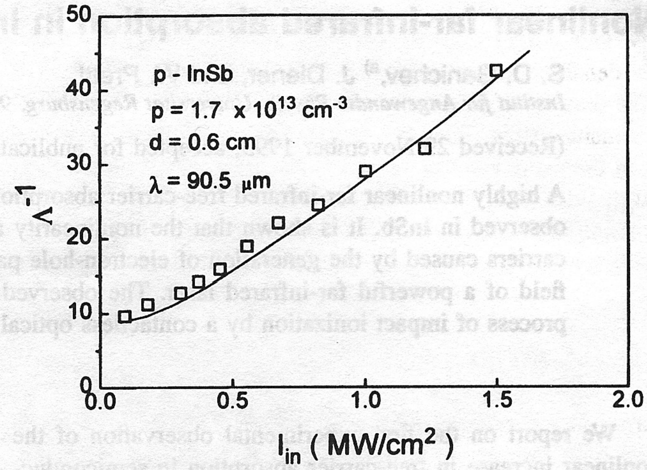

FIG. 3. Reciprocal transmission $\Lambda^{-1}=I_{in}/I_{out}$ as a function of the intensity of light I_{in} ($\lambda=90.5$ μm) entering the crystal for $p-$InSb at $T=77$ K with $p=1.7\times10^{13}$ cm^{-3} of thickness $d=0.6$ cm. Solid lines are calculations following Eqs. (1)–(4) with $E_c=1.2\times10^4$ V/cm.

Other mechanisms like multiphoton absorption[10] and photon[11] or phonon[12] assisted tunnelling as well as direct tunnelling[10,13] in the electric field of radiation, which all lead to an increase of the absorption with rising intensity, may be ruled by the wavelength dependence. In all these cases, at a constant level of intensity, the nonlinearity gets smaller or does not change with increasing wavelength. This is in contrast to the present observations which show the opposite wavelength dependence.

Interband transitions by radiation with photon energies $\hbar\omega\ll E_g$ are caused by electrons (or holes) heated in the field of the high-power optical wave. In the high-frequency electric field of an optical wave the electrons (holes) acquire high energies entirely because of collisions, which is quite different from the case of heating in the static or low frequency ($\omega\tau\ll1$) field case. To be specific, we will consider n-type material in the following. The number of generated electron-hole pairs, $\Delta n=\Delta p$, is given by[9]

$$\Delta n(E)=\Delta p(E)=An\ \exp(-E_c^2/E^2), \tag{1}$$

where

$$E_c=\frac{3\hbar\omega_0\omega^2 m^*}{e^2}\int_{\hbar\omega_0}^{E_g}\frac{(2\epsilon+E_g)^2}{\epsilon(\epsilon+E_g)}\times\ln\frac{4\epsilon(\epsilon+E_g)}{\hbar\omega_0(2\epsilon+E_g)}\frac{d\epsilon}{E_g} \tag{2}$$

A is a constant, n is the dark density of carriers, E and E_c are the radiation fields and a characteristic electric field, correspondently, $\hbar\omega_0$ is the optical phonon energy, e is the electron charge, and m^* is an effective mass.

As the free-carrier absorption is proportional to the number of carriers, the generation of electron-hole pairs leads to an increase of the sample absorption as a function of intensity, $K(I)$, which is the higher the more carriers are produced. The absorption coefficient $K(I)$ can be determined as

$$K(I)=n\sigma_n+\Delta n(I)\ \sigma_n+\Delta p(I)\ \sigma_p, \tag{3}$$

where $\sigma_{n,p}$ are absorption cross sections of electrons or holes, and $\Delta n(I)=\Delta p(I)$ are photoinduced electrons and holes densities, respectively. As it is seen from Eq. (1) and (2) the number of generated carriers related to the dark carrier density, $\Delta n/n$, does not depend on the dark density n and, at the same level of radiation intensity, $\Delta n/n$ increases strongly with decreasing radiation frequency as $E_c \propto \omega^2$. As it was mentioned above, the observed nonlinearity shows the same behavior. Integrating the differential Lambert–Bouguer law

$$dI/I=-K(I)dx, \qquad (4)$$

where x is a coordinate in the direction of radiation propagation with the absorption coefficient $K(I)$ determined by Eqs. (1) and (3), the dependence of Λ^{-1} on the radiation intensity has been calculated. The values of σ_p, σ_n have been obtained from independent experiments of the absorption at low intensities for all samples. To determine the values of $\Delta n(I)$, $\Delta p(I)$, additional measurements of the photoconductivity have been made by applying the method described in Ref. 9. Figure 4 presents one of the experimental dependences of the number of additional carriers on the reciprocal of the square of the field in the interband impact ionization region for an InSb sample with $n=3.8\times 10^{15}$ cm^{-3} at the wavelengths of 90.5 and 250 μm. In Figs. 1–3, the calculated relations between I_{in} and Λ^{-1} are shown by lines. It is seen that the experimental results and the results of calculations are in excellent agreement. We emphasize that all necessary parameters have been obtained from independent measurements and the calculations are not based on any kind of fitting.

In summary, we have observed a lightly nonlinear absorption of far-infrared radiation caused by heating of carriers in the strong electric field of an optical wave producing impact ionization which in turn leads to electron-hole pair generation. The good agreement between measurements and calculations suggests the use of this effect as a contact-less optical method to study the process of impact ionization in semiconductors.

One of the authors (S.D.G.) thanks the Alexander von Humboldt Foundation for the support of his work. Financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

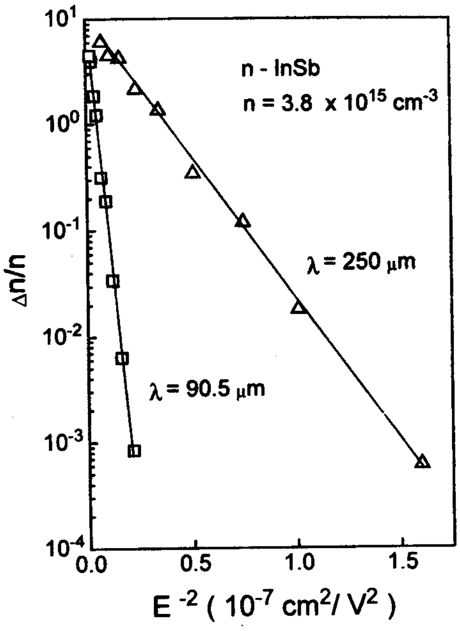

FIG. 4. Normalized density of additional carriers $\Delta n/n$ measured by photoconductivity as a function of the reciprocal of the square of the field in the interband impact ionization region for an n-InSb sample with $n=3.8\times 10^{15}$ cm^{-3} and two wavelengths: 90.5 μm (squares), 250 μm (triangles).

[1] P. T. Landsberg, J. Appl. Phys. **74**, 1451 (1993).
[2] F. Capasso, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic Press, New York, 1985), Vol. 22, part D.
[3] A. Brandl and W. Prettl, Phys. Rev. Lett. **66**, 3044 (1991).
[4] A. M. Kahn, D. J. Mar, and R. M. Westervelt, Phys. Rev. B **45**, 8342 (1992).
[5] V. V. Mitin, Appl. Phys. A **39**, 123 (1986).
[6] A. R. Beattie, Semicond. Sci. Technol. **7**, 401 (1992).
[7] J. Bude and K. Hess, Phys. Rev. B **45**, 10958 (1992).
[8] S. M. Cho and H. H. Lee, J. Appl. Phys. **71**, 1298 (1992).
[9] S. D. Ganichev, A. P. Dmitriev, S. A. Emel'yanov, Ya. V. Terent'ev, I. D. Yaroshetskii, and I. N. Yassievich, Zh. Eksp. Theor. Fiz. **90**, 445 (1986), [Sov. Phys. JETP **63**, 256 (1986)].
[10] L. V. Keldysh, Zh. Eksp. Theor. Fiz. **47**, 1945 (1964) [Sov. Phys. JETP **20**, 1307 (1965)].
[11] P. S. S. Guimaraes, Brian J. Keay, Jann P. Kaminski, S. J. Allen, Jr., P. F. Hopkins, A. C. Gossard, L. T. Florez, and J. P. Harbison, Phys. Rev. Lett. **70**, 3792 (1993).
[12] S. D. Ganichev, W. Prettl, and P. G. Huggard, Phys. Rev. Lett. **71**, 3882 (1993).
[13] S. D. Ganichev, J. Diener, and W. Prettl (unpublished).