Nonlinear Far-Infrared Absorption in InSb due to Light Impact Ionization.

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Abstract

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.

Introduction

We report on the first experimental observation of the nonlinear increase in free carriers 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 $A^{III}B^{IV}$ semiconductor compounds and in their solid solutions are currently attracting considerably attention. 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 fibre-optic communication systems [2]. Additionally the autocatalytic nature of impact ionisation leads to impurity breakdown and the formation of dynamic structures in high purity materials.

Recently impact ionization has been observed in the high frequency electric field of an optical wave in the opposite limit $\omega\tau > 1$ [3]. 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.

Experimental set up and results

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 at T = 77 K with carrier densities n (p) in the range of 10^{13} cm^{-3} to 5 10^{15} cm^{-3}. The intensity of incident and transmitted radiation was measured by fast far-infrared photon drag and intraband photoconductivity detectors made of n-type Ge (ARTAS models PD-5F and IPA-2F; time resolution better than 0.5 ns). The radiation sources used were pulsed FIR NH_3 and CH_3F molecular lasers optically pumped by a TEA CO_2 laser providing 40 ns pulses, at the wavelengths λ= 90.5 µm, 152 µm and 250 µm. The maximum intensity of radiation in the sample was 3 MW/cm^2. 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 sample at T=77K resulted in an increasing of the radiation absorption in the samples. The reciprocal transmission, $\Lambda^{-1} = I_{in}/I_{out}$, 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. Nonlinear absorption has been observed with all p- and n-type samples and for all carrier densities. Fig. 1, 2 show the dependence of Λ^{-1} on I_{in} obtained in n-InSb with n equal $1 \cdot 10^{13}$ and $3.8 \cdot 10^{15}$ cm^{-3}. It is seen that the Λ^{-1} rises with increasing I 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.

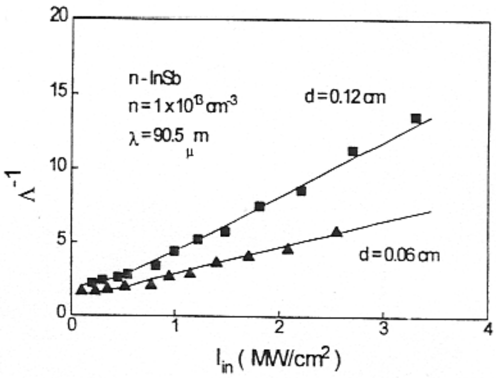

Fig.1. Reciprocal transmission $\Lambda^{-1} = I_{in}/I_{out}$ as a function of the incident radiation intensity I_{in} Solid lines are calculations following Eq.1-3 with E_c=1.3 10^4 V/cm.

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 µm and 250µm. Measurements carried out on p-type InSb basically gave the same results.

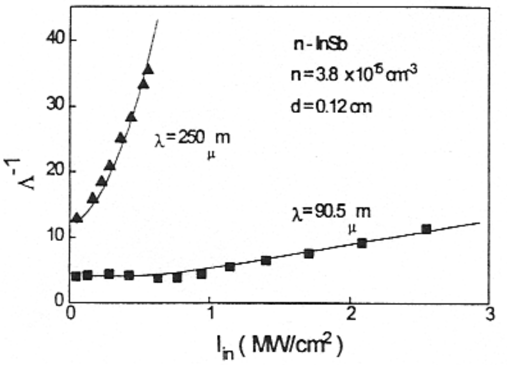

Fig.2. Reciprocal transmission $\Lambda^{-1} = I_{in}/I_{out}$ as a function of the incident radiation intensity I_{in}. Solid lines are calculations following Eq.1-3 with parameters E_c= 2.2 10^4 V/cm (λ=90.5 μm) and E_c= 0.6 10^4 V/cm (λ=250 μm).

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 [3]. Interband transitions by radiation with photon energies $\hbar\omega << E_g$ 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 $\omega\tau >>1$ (τ is the momentum relaxation time) the electrons (holes) acquire high energies entirely because of collisions. The number of generated electron-hole pairs, $\Delta n = \Delta p$, is given by [3]

$$\Delta n(E) = \Delta p(E) = A\, n \exp(-E_c^2 / E^2) \qquad (1)$$

where

$$E_c = B\frac{3\hbar\omega_0\omega^2 m^*}{e^2}, \qquad (2)$$

and A and B are constants, E and E_c are the radiation and a characteristic electric fields, $\hbar\omega_0$ is the optical photon energy.

Generation of free carriers 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 allows us to conclude that the effect is due to 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.

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

$$K = n\sigma_n + \Delta n(I) * \sigma_n + \Delta p(I) * \sigma_p \qquad (3)$$

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. Integrating the differential Lambert-Bouguer law $dI/I = -K(I)dx$, where x is a coordinate in the direction of radiation propagation with the absorption coefficient K(I) determined by Eqs. 1 - 3, the dependence of Λ^{-1} on the radiation intensity has been calculated. The values of $\Delta n(I)$, $\Delta p(I)$ and σ_p, σ_n have been obtained from independent experiments of the photoconductivity, by applying the method described in [3], and absorption at low intensities for all samples. In Figs. 1-2 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 highly 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 contactless optical method to study the process of impact ionization in semiconductors. A more extended version of the results has been published in [4].

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