LIGHT IMPACT IONISATION IN SEMICONDUCTORS

S.D.Ganichev, A.P.Dmitriev, S.A.Emel'yanov,
Ya.V.Terent'ev, I.D.Yaroshetskii, I.N.Yassievich

A.F.Ioffe Physicotechnical Institute,
Academy of Science of the USSR, 194021, Leningrad, USSR

ABSTRACT - The electron-hole pairs generation was observed in a semiconductor by light of photon energy much (tens of times) less than the energy gap of the semiconductor. Luminescence of n-type InSb was observed experimentally in the fundamental absorption region as a result of excitation with the light of the wavelength λ=90.55 μm. Generation of electron-hole pairs was due to the impact ionization caused by electrons (or holes) heated in the field of a high-power optical wave.

We shall report experimental observation of generation of electron-hole (EH) pairs by light incident on a semiconductor when the photon energy $\hbar\omega$ is much (tens of times) less than the energy gap of the semiconductor, $\mathcal{E}_g$, (preliminary results were given in Ref.1). Our radiation source was a high-power pulsed optically pumped NH_3 (D_2O) laser. The emission wavelengths used in our experiments were 90.55, 140, and 385 μm and the pulse duration was 40-100 ns. The intensity of the radiation, I, incident on the sample is varied up to 2 MW/cm^2. The investigation was carried out on n- and p-type InSb samples at T=78K with carriers densities from 10^{13} to 10^{16} cm^{-3}.

A typical oscilogram of the submillimeter photoconductivity (PC) signal at high I has a slow component in the form of a decay process in additional to the fast component (μ-PC). The order of magnitude of the signal decay and the nature of its dependence on the dark-carrier density were similar to the corresponding dependences applicable to the lifetime of nonequilibrium carriers in n,p-type InSb at T=78 K. This led us to the hypothesis that EH-pair generation has occured in our samples. The hypotesis was justiefied by an experiment in which the luminescence of n-type InSb was observed in the fundamental absorption region (λ=5 μm, $\mathcal{E}_g$ =224 meV) when samples were excited with high-power laser radiation of the λ=90.55 μm

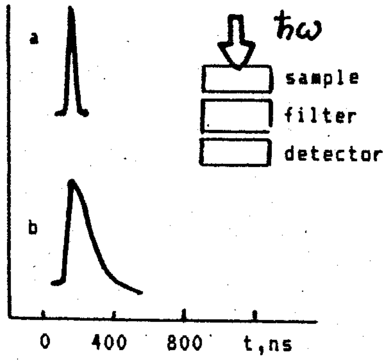

Fig. 1

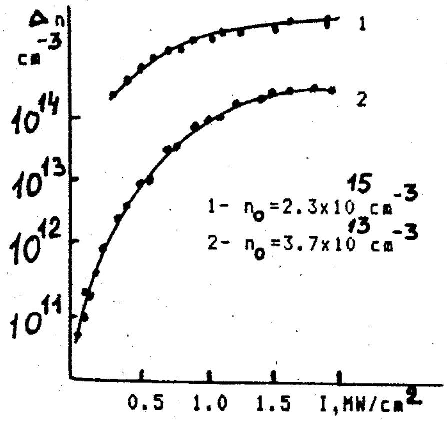

Fig. 2

wavelength ($\hbar\omega$=13.7 meV).Figure 1 shows the scheme of the experement and its result. A Ge:Au extrinsic photodetector with an impurity level at 160 meV was employed. The experimental scheme provieded the absence of the signal from the photodetector even at the highest intensity of the incident light (2 MV/cm^2), when there was no sample at all.

The luminescence was observed for the sample of InSb with n=2.3x10^{15} cm^{-3}. Figure 1 shows the typical oscillograms of the exiting radiation (a) and the luminescence signal (b). The kinetics of the luminescence signal was governed by the nonequilibrium carrier lifetime in InSb at T=78 K when n=2.3x10^{15} cm^{-3}.Therefore, the experimental results confirmed that EH-pairs were generated in our samples. Figure 2 shows the experimental dependences of the nonequilibrium carriers density Δn in n-InSb at T=78K on the intensity of the incident radiation with the λ=90.55μm wavelength, obtained for two values of the dark-carrier density. The excess density was deduced directly from the maximum value of the photoconductivity signal which was associated with the generation of the nonequilibrium carriers. It is show (Fig.2) that the curves are strongly nonlinear and exhibite a quasithreshold dependence on the exciting radiation intensity. A dependence of this type could be only associated with two mechanisms of creation of nonequilibrium electrons: multi-photon interband absorption or impact ionization in the field of a light wave.

Multi-photon interband absorption of light has been investigated in detail [2]. Here, we shall simply mention that in this case the higher the ligh frequency the greater the number of EH-pairs and, naturaly, the later is independent of the dark-carrier densities. Howerer, in the case of impact ionization by carriers heated in the field of a light wave, as it will shown below, the situation should be opposite.

In general, the carrier-density dependence on the number of nonequilibrium electrons, Δn, (Fig.2) supports the second meechanism. However, in order to ensure reliable identification of the pair-generation mechanism, we should carry out additional experiments at two wavelength of a D_2O laser: λ=140μm and λ=385μm These experiments showed that an increase in the radiation wavelength reduced strongly the threshold of generation of excess carriers. This has unambiguously indicated that the generation of EH pairs in our case are due to impact ionization caused by the heating of free carriers in the field of a light wave. Fig. 3a,b shows experimental dependences of $\Delta n/n_o$ on the reciprocal of the square of the amplitude of the electric field E of light wave in a sample of n -type InSb with $n=3.67*10^{13}$ cm^{-3} at three wavelength: 1 -λ=90.55μm, 2 - λ=140μm, 3 - λ=385μm. The dependences are indeed described well by relation

$$\frac{\Delta n}{n_o} = A \exp\left(-E_o^2/E^2\right) \qquad (1)$$

where E_o -is the characteristic field intensity proportional to the frequency of the exciting radiation. It is noted that there are two rectilinear regions with different values of the parameter E_o. Their absolute values of E_{o1} and E_{o2} differ approximately twofold and depend linearly on the frequency of the incident radiation. The exitence of these two regions can be attributed to the interband impact ionization characterized by a threshold energy $\mathcal{E}_i \sim \mathcal{E}_g$ and to the impact ionization of the electron that are localized at impurity (structure defect) level with energy $\mathcal{E}_g/2$ ($\mathcal{E}_i \sim \mathcal{E}_g/2$).

The case of impact ionization in the field of light wave is examined theoretically and the expression for the probability of the light

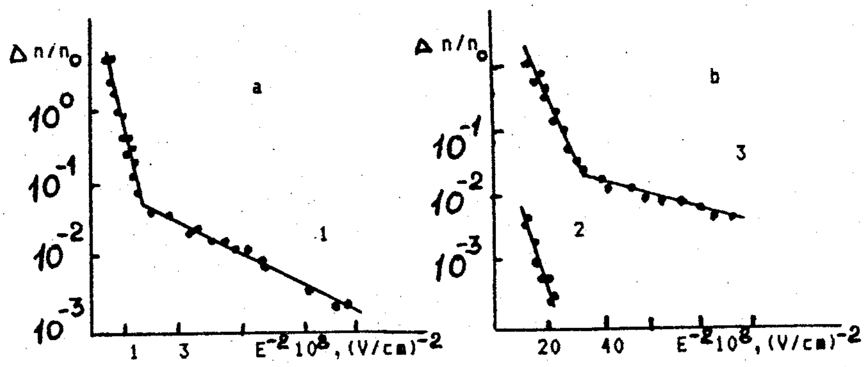

Fig. 3

impact ionization is obtained. Naturally, the inequality $\omega\tau > 1$ (τ is the electron-impulse relaxation time) take place here. It has the form:

$$W(E) = W_{is}\cdot\gamma\cdot\exp(-E_0^2/E^2) \qquad (2)$$

where

$$E_0^2 = \frac{3\hbar\omega_0\omega^2 m^*}{e^2}\int_{\hbar\omega_0}^{\varepsilon_g}\frac{(2\varepsilon'+\varepsilon_g)^2}{\varepsilon'(\varepsilon'+\varepsilon_g)}\ln\frac{4\varepsilon'(\varepsilon'+\varepsilon_g)}{\hbar\omega_0(2\varepsilon'+\varepsilon_g)}\frac{d\varepsilon'}{\varepsilon_g}$$

and $\hbar\omega_0$ - optical phonon energy, γ - preexponential factor, $W_{is}=10^{10}s^{-1}$ - maximum probability of the elementary event of interband impact ionization. It is evident from (2) that $W \sim \exp(-E_0^2/E^2)$, and $E_0^2 \sim \omega^2$ as it was observed in the experiment.

The phenomenon of the impact ionization was also investigated in detail in p-InSb. The analysis of the experimental data show that in p-material the initial stage of the process of the impact ionization is occures due to impact ionization by the light holes. And then, when the number of EH-pairs will be available enough, the process of the impact ionization began to be determined by the nonequilibrium electrons.

REFERENCE

[1] S.D.Ganichev, A.P.Dmitriev, S.A.Emel'yanov, Ya.V.Terent'ev, I.D.Yaroshetskii, and I.N.Yassievich, JETP Lett. 40, 948, (1984).

[2] L.V.Keldysh, Sov. Phys. JETP 20, 1307 (1965).

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