PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON THE PHYSICS OF SEMICONDUCTORS, KYOTO, 1966
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 21, SUPPLEMENT, 1966

VII-7. On the Mechanism of Recombination Radiation of *p-n* Junctions in GaAs

D. N. NASLEDOV and B. V. TSARENKOV

Ioffe Physical Technical Institute, USSR Academy of Sciences, Leningrad, USSR

The present report reviews some investigations of the recombination radiation of GaAs *p-n* junctions carried out at the Electronic Semiconductors Laboratory of the Physical Technical Institute.

§ 1. Kinetics of Radiative Recombination of Non-equilibrium Current Carriers in GaAs *p-n* Junctions

1. The objects of study were *p-n* junctions in GaAs obtained by diffusion of Zn or Cd into *n*-GaAs with an electron concentration of $n_n=10^{17}$ to 10^{18} cm^{-3}.

As is well known,[1] one can isolate several bands in the spectra of recombination radiation of *p-n* junctions in GaAs: short wavelength band 1) $h\nu_{M1}\simeq 1.47$ eV (77°K) and 1.36 eV (293°K); long wavelength band 2) $h\nu_{M2}\simeq 1.25$ eV (77°K)—this band is not observed at room temperature; long wavelength band 3) $h\nu_{M3}\simeq 1.02$ eV (77°K) and 0.97 eV (293°K).

2. We still consider now the radiation intensity of each band as a function of current (Fig. 1).

Tne radiation intensity for *p-n* junctions prepared with *n*-type GaAs having $n_n=10^{17}\sim 5\times 10^{17}$ cm^{-3} depends on current I in different way for different bands Φ_i. At low current densities J (below 5 A/cm^2) Φ_i for each band increases superlinearly with the increase of current, *i.e.*

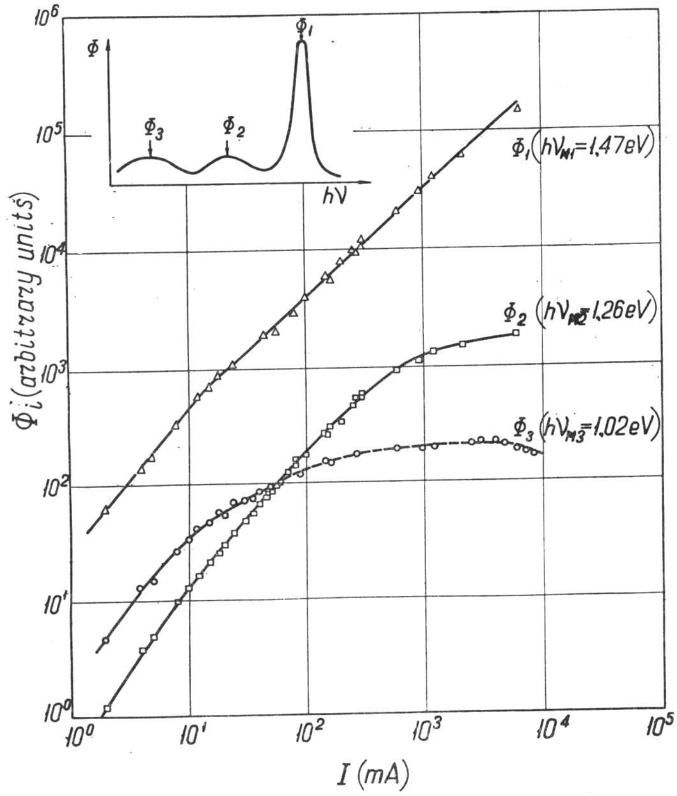

Fig. 1. Current dependence of radiation intensity for different spectral bands at 77°K (area of *p-n* junction about 10^{-2} cm^2).

$\Phi_i \approx I\eta$, where $\eta = 1.5$–2 for different specimens. The radiation intensity of the short wavelength band Φ_1 at $J > 10\ \mathrm{A/cm^2}$, as a rule, increases linearly with increasing current.

The radiation intensity in the long wavelength bands Φ_2 and Φ_3 at 77°K tends to approach saturation with increasing current. For *p-n* junctions prepared from *n*-type GaAs with $n_n = 10^{18}\ \mathrm{cm^{-3}}$ no saturation is observed in the intensity within bands 2 and 3.

3. Let us consider the relaxation of the radiation intensity in each band. If one passes rectangular pulses of direct current through a *p-n* junction, the following phenomena are observed.

Voltage pulses on the diode remain rectangular down to durations of about 10 nsec.

Radiation pulses of short wavelength band 1 also remain rectangular down to durations of about 10 nsec.

Radiation pulses of long wavelength bands 2 and 3 turn out to be non-rectangular already at microsecond current pulses (Fig. 2).

The shape of the long wavelength radiation

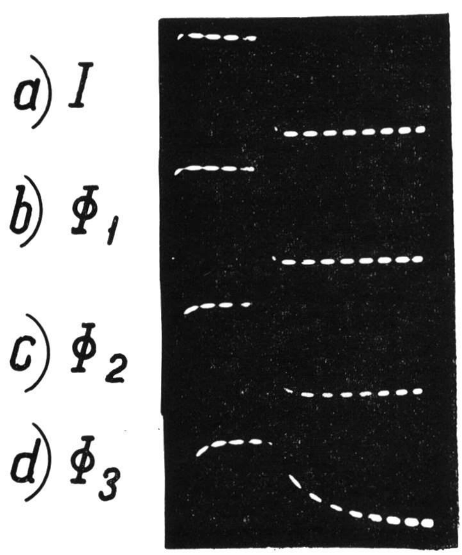

Fig. 2. Oscillographic traces of direct current pulses through a *p-n* junction and of radiation intensity pulses for different spectrum bands at 77°K.

a) current pulse ($I = 400$ mA, $\tau = 50\ \mu$sec);
b) radiation pulse of short wavelength band 1 ($h\nu_{M1} = 1.47$ eV);
c) radiation pulse of long wavelength band 2 ($h\nu_{M2} = 1.27$ eV);
d) radiation pulse of long wavelength band 3 ($h\nu_{M3} = 1.02$ eV).

pulses may be approximated by exponential relationships as follows:

within the region of rise ($t < \tau$)

$$\Phi_i(t) = \Phi_{0i}[1 - \exp(-t/\tau_{ri})]\,,$$

within the region of decay ($t > \tau$)

$$\Phi_i(t) = \Phi_i(\tau) \exp[-(t-\tau)/\tau_{di}]\,,$$

where t is the time reckoned from the beginning of current pulse, τ is the duration of current pulse, τ_{ri}—the time constant of radiation intensity rise, Φ_{0i}—the radiation pulse amplitude at $t \gg \tau_{ri}$, τ_{di}—the time constant of radiation intensity decay.

The time constant of radiation intensity rise τ_r is the same for different parts of spectrum in a band. For longer wavelength radiation (band 3) τ_r is larger than for the shorter wavelength one (band 2). The magnitude of τ_r decreases with increasing current for both bands (2 and 3).

For *p-n* junctions prepared from material with $n_n = (1\text{–}3) \times 10^{17}\ \mathrm{cm^{-3}}$, $\tau_{r3} \simeq 20\ \mu$sec (77°K) and $\simeq 15\ \mu$sec (293°K) at $J \sim 10\ \mathrm{A/cm^2}$ and $\simeq 1\ \mu$sec (77 and 293°K) at $J \sim 100\ \mathrm{A/cm^2}$.

The time constant of radiation intensity decay τ_d for different regions of the spectrum in a band is likewise the same. For longer wavelength band 3, τ_d is larger than for band 2. The τ_d does not depend on current and decreases with increasing temperature. For both bands (2 and 3) τ_d decreases with the increase of electron concentration in the starting material. For *p-n* junctions prepared from material with $n_n = (1\text{–}3) \times 10^{17}\ \mathrm{cm^{-3}}$, $\tau_d = 10-30\ \mu$sec (77°K) and $7-20\ \mu$sec (293°K). For band 3 at small J (below $50\ \mathrm{A/cm^2}$) $\tau_{r3} \simeq \tau_{d3}$, whereas at $J > 50\ \mathrm{A/cm^2}$ $\tau_{r3} < \tau_{d3}$. For band 2 at small J (below $50\ \mathrm{A/cm^2}$) $\tau_{r2} \simeq \tau_{d2} = 2-4\ \mu$sec.

4. It follows from experiments that the time of current and voltage relaxation is several orders of magnitude smaller than the relaxation time of the long wavelength radiation intensity.

This indicates that, first, the current is determined by recombination of carriers not via the deep levels responsible for long wavelength radiation, since these levels do not markedly affect the lifetime of minority carriers in the allowed zone.

Second, the long wavelength radiation arises as a result of recombination of a majority carrier with a minority carrier trapped on a deep level. This is confirmed also by the fact that the time of radiation intensity decay does not depend on injection level and decreases with the increase of concentration of equilibrium majority current carriers in p- and n-regions of a p-n junction.

The decrease of the time constant with the rising of long wavelength radiation and the tendency of this radiation intensity to saturation with increasing current is due to the filling of deep levels at the increase of current.

§ 2. A Comparative Study of Recombination Radiation of GaAs p-n Junctions with and without a Fabri-Perot Cavity

1. There were studied diodes whose p-n junctions had been prepared by diffusion of Zn into Te-doped n-type GaAs with electron concentration of $7\times 10^{17}-3\times 10^{18}\,\mathrm{cm}^{-3}$, the area of a p-n junction being about $10^{-3}\,\mathrm{cm}^2$.

The original diodes had two parallel mirrored faces perpendicular to the plane of the p-n junction; two other faces were grinded (a Fabry-Perot cavity). There were measured the dependences of the halfwidth δ and of the energy at the maximum $h\nu_M$ of the main radiation band on the density of current $\boldsymbol{J}$ through a given p-n junction with and without a Fabry-Perot cavity. On measuring the parameters of a diode with cavity, the mirrored faces of the diode were etched, after which the same measurements were repeated without the cavity. One recorded here the radiation leaving the diode parallel to the p-n junction plane on the mirror side, and after etching the mirrors—on the same side.

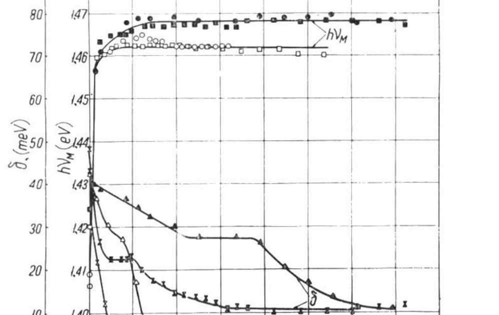

Fig. 3. Halfwidth δ and energy at the maximum $h\nu_M$ of the main radiation band as functions of the density of current J through GaAs p-n junction with Fabry-Perot cavity and through the same p-n junction without cavity (open circles diode with mirrored faces, full circles-diode after etching).

2. The results of the experiment are as follows.

Throughout all the current density range covered, the dependence $\delta=f(\boldsymbol{J})$ for a diode without cavity has three clearly defined regions: a fall-off at low current densities (the primary spectral narrowing), a plateau and one more fall-off at high densities (the secondary spectrum narrowing); $h\nu_M$ varies from 1.41 eV to about 1.47 eV, and at the secondary spectrum narrowing $h\nu_M$ of a diode without cavity remains practically unchanged; $h\nu_M$ corresponding to the primary narrowing is smaller than $h\nu_M$ corresponding to the secondary narrowing or to $h\nu_M$ of coherent radiation (Fig. 3).

3. From the fact that δ decreases with increasing current starting from quite low values of $\boldsymbol{J}$ (the primary narrowing) one may draw two conclusions.

One is that, one may suppose that already at low $\boldsymbol{J}$ the emission acquires a stimulated nature, in other words, an inversion of population of some allowed states is realized in the semiconductor.

The other is that it may be supposed that there is no stimulated emission, and the primary narrowing occurs as a result of a displacement over some allowed states of the Fermi quasi-level for minority carriers whose effective mass increases with increasing injection level.

The fact that within the primary narrowing region δ of a diode with cavity is smaller than δ of a diode without cavity at the same current densities permits to conclude that we have here stimulated emission.

From the fact that $h\nu_M$ corresponding to the primary narrowing is smaller than $h\nu_M$ for the secondary narrowing it may be concluded that the primary spectrum narrowing occurs as a result of population inversion not of those allowed states which are responsible for the secondary spectrum narrowing, *i.e.* for the conventional stimulated and coherent emission peaked at $h\nu_M\simeq 1.47$ eV.[1,2] The allowed states responsible for the primary spectrum narrowing probably may be "tails" in the energy gap.

§ 3. Change of the Voltage-Current Characteristic of a GaAs Laser at a Transition from Amplification of Radiation to Lasing

1. There were studied diodes with p-n junc-

tions prepared from Te-doped n-type GaAs with $n_n \simeq 2\times10^{18}$ cm^{-3}, the p-region being doped with Zn and the area of p-n junction being $\simeq 10^{-3}$ cm^2.

The diodes had two parallel mirrored faces perpendicular to the plane of the p-n junction, two other faces being grinded (the Fabry-Perot cavity).

There were measured the current through p-n junction I as a function of diode voltage U and the spectral distribution of radiation intensity Φ at different currents.

2. The results of the experiments are as follows.

At diode voltages $U > E_g/e$ (E_g being the width of the energy gap in GaAs, e—the electron charge) the I-U characteristic has two linear regions with a sharp transition from one to another, in other words, there appears an inflection in the I-U characteristic (Fig. 4).

If we correlate the I-U characteristic (Fig. 4) with the spectral distribution of radiation intensity at different currents (Fig. 5) we shall see that the inflection in the I-U characteristic occurs at the transition from radiation amplification to lasing, *i.e.* the inflection current $I_b = I_1$ which is the threshold of coherent emission (Figs. 4 and 5).

The cutoff voltage (determined by extrapolating the linear dependence I-U to $I=0$) corresponding to the first linear region. $U_{01} = 1.47 \pm 0.01$ V. The energy at the maximum of the main radiation band $h\nu_M = (1.46\text{–}1.47) \pm 0.005$ eV, *i.e.* $U_{01} \simeq h\nu_M/e$.

The differential resistance R_{S2} ($R_S = \partial U/\partial I$ within the linear region of the I-U characteristic) corresponding to the second region of the I-U characteristic (after the inflection) is a factor of 1.2–1.5 smaller than R_{S1} corresponding to the first region of the I-U characteristic (before the inflection).

If we mechanically grind the mirrors of the laser cavity, in other words, if we damage them, both lasing and the inflection in the I-U characteristic at I_1 disappear.

Thus it follows from the experiment that the linear characteristic I-U of a laser undergoes inflection at a transition from the amplification of emission to lasing, *i.e.* that R_S changes here practically stepwise and does not depend on the current before and after the onset of lasing.

3. Let us consider the reason for such inflection in the I-U characteristic.

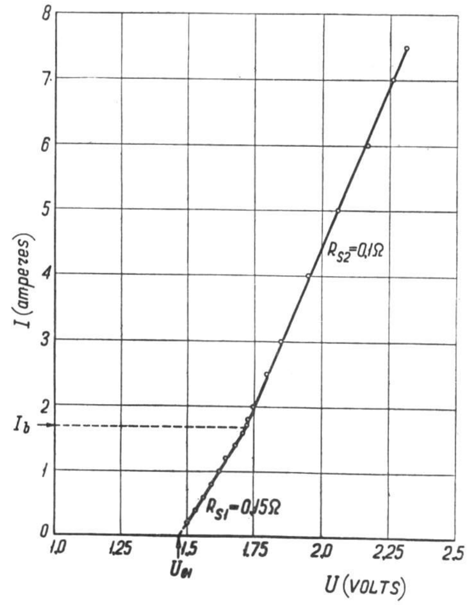

Fig. 4. The current vs. voltage characteristic of diode 15 at 77°K before and after the onset of lasing.

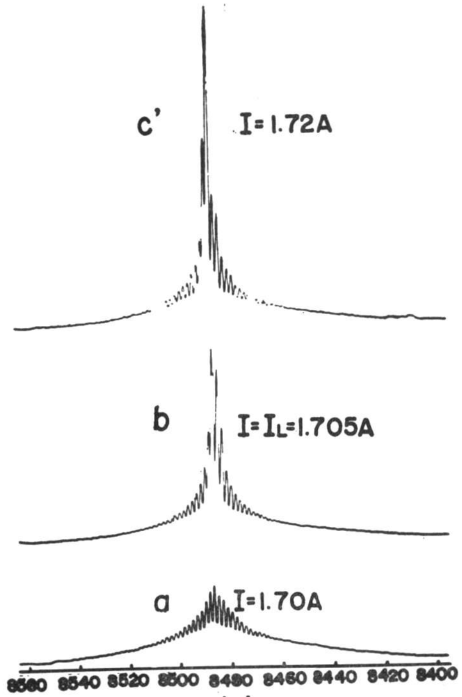

Fig. 5. Sepctral distribution of radiation intensity of diode No. 15 at different currents.
a) before lasing ($I = 1.70$ A);
b) at the threshold of lasing ($I = 1.705$ A);
c) after the onset of lasing ($I = 1.72$ A).
(the vertical scale being the same in all cases).

The most probable reason for the decrease of R_S at $U > E_g/e$ is the increase of current carrier concentration in the bulk as a result of intrinsic photoeffect caused by photons which are emitted due to recombination of nonequilibrium carriers.

Before the onset of lasing the light propagates mainly perpendicular to the plane of the *p-n* junction. Here only a small fraction of photons can cause photoeffect in the *p*-region, and the major number of photons is absorbed by free holes. Therefore when light propagates perpendicular to the *p-n* junction plane, R_S does not change with increasing current.

After the onset of lasing, light propagates mainly parallel to the *p-n* junction plane. Now the light localizes in the vicinity of the space charge layer within a region of about some microns in size, *i.e.* in the nondegenerate part of the *p*-region where photoeffect can take place. As a result of the photoeffect, the concentration of carriers increases sharply, and this part of the *p*-region is excluded from the total resistance. Therefore an inflection occurs in the *I-U* characteristic.

References

1) D. N. Nasledov, A. A. Rogachev, S. M. Ryvkin and B. V. Tsarenkov: Fiz. tverdogo Tela **4** (1962) 1062.

2) R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys and R. O Carlson: Phys. Rev. Letters **9** (1962) 366.