# Measurement of the rate of exciton condensation into electron-hole drops in germanium

I. M. Fishman

*A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences*

(Submitted 16 October 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 10, 644–648 (20 November 1978)

A method is proposed for measuring the rate of condensation as a function of the degree of supersaturation of the exciton gas. The results agree with the classical theory at a small degree of supersaturation, and differ in the case of a large degree.

PACS numbers: 71.35. + z

A unique hysteresis effect was observed in Ref. 1 in the action of a microwave field on an excitons + EHD system in germanium. If the sample is exposed to microwave radiation after the drops have already been produced in it, then the intensity of the EHD luminescence increases slightly because of the increase in the flux of the electrons and holes that stick to the drops. On the other hand, if the generation rate $G$ is increased gradually when the microwave field is turned on, then the condensation threshold of the excitons is reached at a faster generation rate, since the microwave field, by heating the free electrons, shifts the point of equilibrium in the system of excitons, electrons, and holes. Thus, there is a range of excitation levels in which the heating field has little effect on the produced drops, but no new drops can be produced. This effect is the basis of the method proposed here for determining the condensation rate.

So long as there are no drops in the sample, the free carriers are generated by the light and are bound into excitons: $G = (n_e/\tau_e) + (n/\tau)$, and the ratio between $n_e$ and $n$ is determined by the coefficient of the binding of the free carriers into excitons; this coefficient depends on the carrier temperature, i.e., on the microwave field intensity. In a heating field, the concentration of the free carriers increases and that of the excitons decreases. Assume that the microwave field is turned off pulsewise for times $\theta$, and the intensity of the exciting light is slowly increased at the same time (Fig. 1).

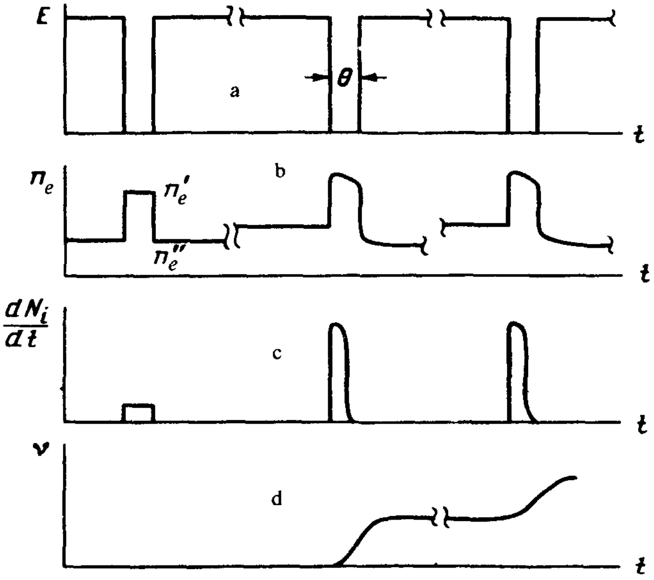

FIG. 1. a) Dependence of the microwave field intensity on the time; $\theta$ is the duration of the microwave field off-pulse. b) Change of concentration of the excitons in the case of a slow increase of the generation rate: $n_e'$ —concentration of the excitons in the "cold" system, $n_e''$—concentration of the excitons in the presence of a microwave field. c,d) Time dependences of the rate of condensation $dN_i/dt$ and of the total concentration $v = (4\pi/3)n_0N_iR^3$ of the condensed phase.

As seen from Figs. 1a and 1b, in each pulse the system returns for a time $\theta$ to the "cold" state. With increasing $G$, an instant is reached when an EHD nucleation center is produced during the time $\theta$, and if the pulse duration is long enough, this germ manages to grow to macroscopic size. Then, after the pulse is turned off, the drop remains in the crystal, but no new nucleation centers can be produced prior to the arrival of the next pulse (Figs. 1c and 1d). The larger $\theta$, the shorter the $G$ at which the condensation should begin. Since the threshold of the appearance of radiation corresponds to a situation wherein at least one viable nucleation center is produced in the crystal during the time $\theta$, the quantity $\theta^{-1}$ takes on the meaning of the minimum rate of condensation at a given degree of supersaturation; therefore, by measuring the threshold pump $G_+$ as a function of the pulse duration we can determine the connection between the condensation rate $dN_i/dt \sim 1/\theta$ and the degree of supersaturation.[2,3]

In the experiment we use samples of pure $n$-Ge($N_d N_a \approx 3\times 10^{10}$ cm$^{-3}$),[1)] which were placed in a short-circuited segment of an 8-mm-band waveguide.[1] The microwave power was turned off in pulses of duration $10^{-3}$–$10^{-7}$ sec, applied to the cathode of a klystron.

The results of the experiment are shown in Fig. 2. Curves 1 and 2 are the ascending and descending branches of the hysteresis curve of the drop-radiation intensity $I(G)$ in the absence of a microwave field. The vertical segments on curves 1 and 2 show how the intensity of the EHD radiation increases with increasing field intensity $E$ up to ~5 V/cm. Curves 4a–4e were recorded at $E \approx 3$ V/cm and at different durations of the microwave-field off-pulses. The hysteresis of the EHD radiation in the microwave field ($\theta = 0$) is represented by curves 3 and 5. It is seen that when $\theta$ decreases from $10^{-3}$ to $10^{-5}$ sec the threshold of the onset of the EHD increases gradually; near the threshold, the exciton concentration is sufficient to produce within the time $\theta$ one or several drops, and each succeeding pulse eliminates the small supersaturation that is produced in the sample because of the increase of $G$ in the interval between the pulses.

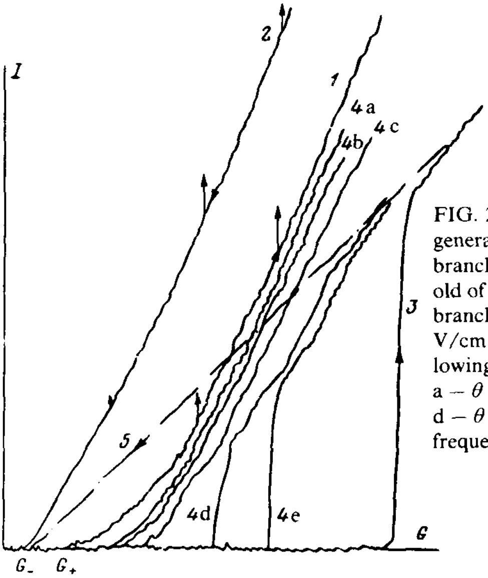

FIG. 2. Dependence of the EHD radiation intensity on the generation rate $G$: 1, 2—forward and reverse hysteresis branches in the absence of a microwave field, $G_+$ —threshold of the ascending branch, $G$ —threshold of descending branch; 3, 5—the same at a microwave field intensity $E \approx 3$ V/cm; 4—ascending branch at $E \approx 3$ V/cm and at the following variation of the duration $\theta$ of the off-pulse time a – $\theta = 10^{-3}$ sec, b – $\theta = 10^{-4}$ sec, c – $\theta = 10^{-5}$ sec, d – $\theta = 10^{-6}$ sec, e – $\theta = 4\times 10^{-7}$ sec; pulse repetition frequency 0.5 Hz, time required to plot one curve ~5 min.

Since the threshold exciton concentration $n_{e\,\mathrm{min}}$ in the "cold" system is proportional to the generation rate $G$, it is possible to determine the dependence of $\theta$ on the degree of supersaturation. It is known that in the classical model[2,3] the rate of condensation depends exponentially on the degree of supersaturation

$$\frac{dN_i}{dt} = A \exp\left(-\frac{\Lambda(T)}{\ln^2 n_e/n_{T\infty}}\right);$$

it is therefore convenient to plot the obtained data in terms of the coordinates $\ln\theta^{-1} = f(\ln^{-2}[n_e/n_{T_\infty}])$ (Fig. 3). The degree of supersaturation $n_e/n_{T_\infty}$ was determined from the ratio $G_+/G_-$ (Fig. 2), with allowance for the fact that $G_-$ corresponds to $n_{e\,\mathrm{min}}$—the minimal exciton concentration compatible with the existence of drops of radius $R_{min}$ at the given temperature; the ratio $n_{e\,\min}/n_{T\infty}$ was determined from the known formulas of Refs. 2 and 3. Curves 1 and 2 of Fig. 3 pertain to the temperatures 1.53 and 1.85 K, respectively. It is seen that the point corresponding to small supersaturations (to large $\theta$) are well described by the straight lines $\theta^{-1} = A - [A(T)/\ln^2(n_e/n_{T\infty})]$; the slopes of these lines determine the coefficient of the surface tension, $\sigma = (2.3\text{–}2.6)\times 10^{-4}$ Oe/cm$^2$, in good agreement with other measurements.[4]

The intercepts of the lines in Fig. 3 with the ordinate axis determine the pre-exponential factor in (1): $A \approx 10^{20}$ sec$^{-1}$ at 1.5 K; this value can be reconciled with the theory[2,3] under two different assumptions: a) if the nucleation centers are produced on impurity centers with binding energy $\sim 1$ MeV, then the concentration of the centers should be $\sim 10^{10}$ cm$^{-3}$; b) if the condensation is homogeneous,[3] then $A$ is determined by the state density $D$ of the "gas of critical nucleation centers": $D = (\nu m^* kT/2\pi\hbar^2)^{3/2}$, $\nu$ is the number of particles in the critical nucleus.

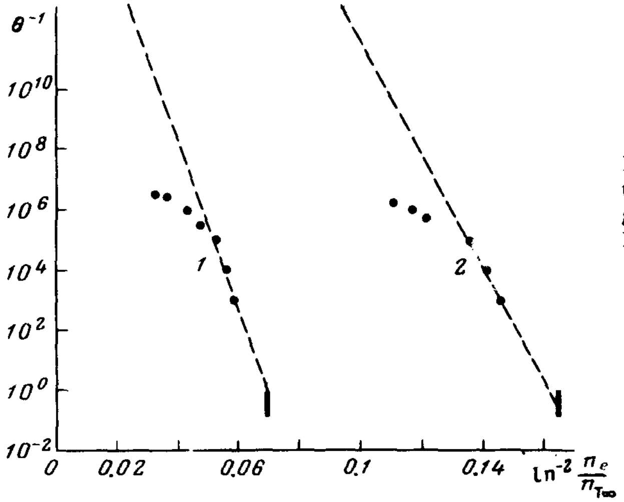

FIG. 3. Dependence of the condensation rate $dN_i/dt = \theta^{-1}$ on the degree of supersaturation: 1 – $T = 1.53$ K; 2 – $T = 1.85$ K.

Starting with $\theta \lesssim 10^{-6}$ sec, the condensation threshold increases sharply with decreasing length of the pulse, and the function $\theta^{-1} = f[\ln^{-2}(n_e/n_{T\infty})]$ deviates from the theoretical one. Jumps appear in this case in the EHD radiation intensity near the condensation threshold (a similar jumplike change of the radiation intensity, which attests to rapid and simultaneous onset of a large number of nuclei, was observed also for a stationary applied microwave field[2]).

The physical meaning of this effect (a detailed discussion is outside the scope of the brief communication) is that the average number of the excitons that collide with the center during the small time interval is not sufficient to produce a critical nucleation center. In other words, it is necessary that the product $n_e\theta$ reach a certain definite value $\delta$. Since the rate of condensation increases very rapidly with increasing $n_e$, by the instant that the condition $n_e\theta > \delta$ is satisfied the number of simultaneously produced nuclei turns out to be very large.

The author thanks B.M. Ashkinadze for useful discussions and for help with the work.

1) The author is most grateful to E. Haller (Lawrence Berkeley Laboratory, USA) for supplying the germanium sample.

2) We note that optical hysteresis of the condensation in a microwave field increases strongly, since the threshold of the descending branch $G$ does not change. The ratio $G_{+}/G_{-}$ can reach values 20–50.

---

[1] N.M. Ashkinadze and I.M. Fishman, Fiz. Tverd. Tela (Lengingrad) **20**, 1071 (1978) [Sov. Phys. Solid State **20**, 619 (1978)].

[2] V.S. Bagaev, N.V. Zamkovets, L.V. Keldysh, I.N. Sibel'din, and V.A. Tsvetkov, Zh. Eksp. Teor. Fiz. **70**, 1501 (1976) [Sov. Phys. JETP **43**, 783 (1976)].

[3] R.M. Westervelt, Phys. Status Solidi B **74**, 727 (1976).

[4] Y.C. Hensel, T.G. Phillips, and G.A. Thomas, Solid State Phys. **32**, (1977).