# Electrical domains and far-IR emission in uniaxially deformed *p*-Ge

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A study has been made of how the formation of electrical domains in *p*-Ge during uniaxial compression affects the far-IR emission of hot holes. In strong electric fields, the intensity of the spontaneous emission is controlled by the length of a domain. A domain instability and the stimulated far-IR emission are shown to affect each other.

## 1. INTRODUCTION

The previously observed[1] stimulated far-IR emission of hot holes in a uniaxially deformed germanium is apparently due to a population inversion of valence subbands split by the compression. We also know that uniaxial compression of *p*-Ge gives rise to a negative differential conductivity. This negative conductivity is due to transport of hot holes into a higher-lying subband, in which they have a greater mass and, correspondingly, a low mobility along the compression direction. A fluctuation-induced instability of the negative differential conductivity of a homogeneous sample leads in turn to the formation of electrical domains. The possibility of a negative differential conductivity in uniaxially deformed Ge was predicted by Ridley and Watkins.[2] Kastal'skiĭ and Ryvkin[3] have observed the onset of Gunn oscillations at liquid-helium temperature. Subsequent studies have revealed Gunn oscillations in compressed *p*-Ge at higher temperatures: 27–160 (Ref. 4) and 77 K (Ref. 5).

In this paper we are reporting a study of the effect of the formation of electrical domains on the spontaneous emission and the interaction between strong-field domains and the stimulated emission at liquid-helium temperature. The test samples and the experimental conditions were the same as in Ref. 1. The pressure $P$ and the electric field $E$ were applied along the [111] crystallographic direction. One or two probe contacts were deposited on a lateral face of a sample, between the main current electrodes, in order to monitor the field nonuniformity. Probes of two types were used: galvanic and capacitive. The capacitive probe was a strip of metal foil 0.5 mm wide, insulated from the sample surface by a thin mica plate. The capacitive probes were used to study the stimulated emission, since they do not distort the field distribution in the sample, and they do not disrupt the resonance conditions.

## 2. STATIC DOMAIN

In an electric field corresponding to the region of a negative differential conductivity on the current-voltage characteristic of a homogeneous sample, either a moving or static strong-field domain can arise, depending on the conditions at the current contacts and on the distance between the latter (more precisely, on the relation between the length of the sample, $L$, and the length scale of the carrier drift caused by the electric field, $v\tau_M$, where $v$ is the drift velocity, and $\tau_M$ is the differential Maxwellian relaxation time) (Ref. 6, for example). In the former case one observes oscillations in the current; in the latter, one finds a current-saturation region on the current-voltage characteristic of the sample. The field distribution in a sample with static domain is stepped; the field outside a domain in a long sample ($L > v\tau_M$) must be the same as the field at the peak of the current-voltage characteristic of the homogeneous sample.[6] In this case the strong-field region (the static domain) should be near the anode in an *n*-type crystal and near the cathode in a *p*-type crystal. The reason for the current saturation is that an increase in the applied voltage is accompanied by an increase in the length of the strong-field region, while the field strengths outside and inside a domain do not change.

Figure 1a shows the average field at a probe, $E_p$ (the voltage on the probe, divided by the distance from the probe to the grounded electrode, which is the anode in the case at hand), as a function of the average field in the sample, $U/L$, where $U$ is the applied voltage. The inset in this figure shows the arrangement of the electrodes and the polarity of the voltage pulse. At pressures $P<4$ kbar (curve *1* in Fig. 1a) the field distribution in the sample remains uniform over the entire range studied (up to 3 kV/cm). Beginning at $P\simeq 4$ kbar (curves *2–4* in Fig. 1a), there is a voltage interval in which $E_p$ remains essentially constant. In this case the current through the sample also reaches saturation (curves *2* and *4* in Fig. 1b; the arrows show the threshold for domain formation). The voltage on the probe begins to reach saturation at the same overall voltage as that corresponding to current saturation. The fact that the field near the anode remains constant shows that a static domain forms near the cathode, and the voltage drop across this domain increases linearly with increasing applied voltage. The saturation value of $E_p$ is the field $E_0$ outside the domain. The fact that the domain lies near the cathode shows that $E_0$ corresponds to the field at the peak of the current-voltage characteristic of the homogeneous sample. If the current contacts are interchanged, the domain forms near the other contact, which is the cathode in this case. The field outside the domain does not change, indicating that the contacts are identical and very "ohmic." It can be seen from Fig. 1a that the field $E_0$ outside a domain decreases with increasing pressure.

The voltage on a probe begins to increase (curve *4* in Fig. 1b at $U/L>2.5$ kV/cm) when the domain fills the entire region between the cathode and the probe. Measurements with a probe at various distances from a current

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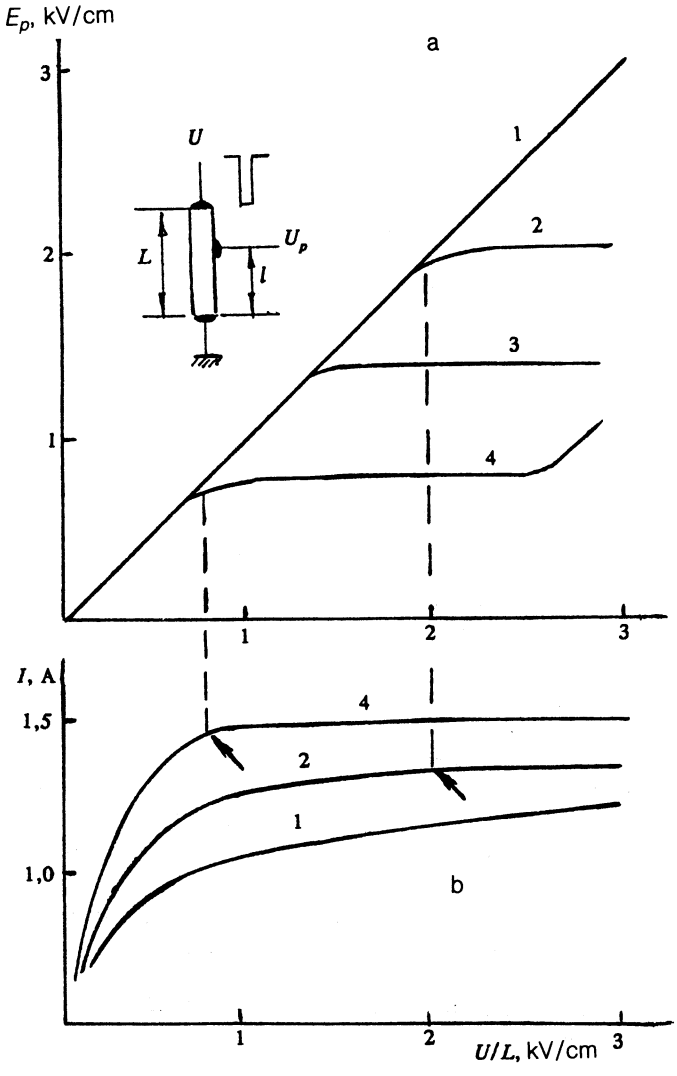


FIG. 1. Plots of (a) the probe voltage divided by the distance from the probe to the anode, $E_p=U_p/l$, and (b) the current through the sample, versus the average field in a sample, $U/L$, for various pressures $P$, kbar: *1*—0 and 2.5; *2*—4; *3*—5; *4*—6.

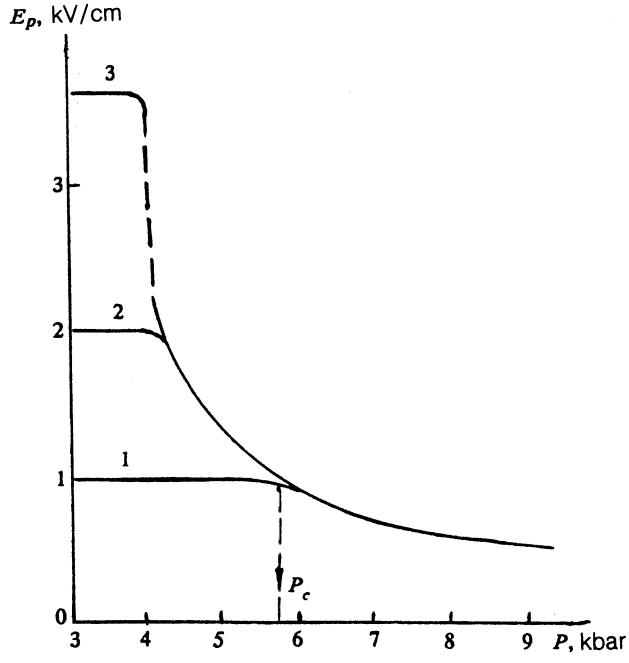


FIG. 2. Average field in the anode region of the sample, $E_p$, versus the pressure, for various values of $U/L$, kV/cm: *1*—1; *2*—2; *3*—3.5.

contact showed that the domain is a region with a strong field $E_d$ which is essentially constant in magnitude, and that this region has a fairly sharp boundary. It can thus be assumed that the field distribution in the sample is stepped and that we have

$$U=E_d d+E_0(L-d), \tag{1}$$

where $d$ is the length of the domain. Knowing the voltage at which the length of the domain becomes equal to the distance from the cathode to the anode, we can determine the field $E_d$ in the domain. It turns out to be 5–7 kV/cm for the various samples.

Figure 2 shows the average field in the sample near the anode as a function of the pressure for various fixed applied voltages. At first, $E_p$ is independent of $P$ and equals the average field in the sample. Beginning at a certain critical pressure $P_c$ (which is shown for curve a in Fig. 2), whose value is lower at higher voltages, a static domain forms in the sample, and the voltage on the probe gives us the field $E_0$ outside the domain. This field decreases with increasing $P$.

The plot of $E_p(P)$ can be understood by looking at the changes in the shape of the current-voltage characteristic as the pressure is varied (Fig. 1b). We see from this figure that the current begins to reach saturation (a region of a negative differential conductivity begins to form on the current-voltage characteristic of a homogeneous sample) at a higher pressure, so $E_0$ decreases. At a fixed voltage, the sample remains homogeneous as long as the field corresponding to the peak of the current-voltage characteristic is lower than the average field in the sample. At $P=P_c$, at which point we have $U/L\simeq E_0$, a domain forms. We see from expression (1) that the length of the domain is

$$d=\frac{U-E_0L}{E_d-E_0}. \tag{2}$$

It is easy to see that as the pressure is raised the length of the domain should increase because of the decrease in $E_0$ (since $U/L<E_d$), beginning at $d=0$ in the case $P=P_c$.

When the voltage across the sample is sufficiently high (curve *3* in Fig. 2), the field $E_p$ falls off sharply at $P\simeq 4$ kbar. The meaning here is that this is the pressure at which the region of negative differential conductivity appears on the current-voltage characteristic of the homogeneous sample.

### 3. SPONTANEOUS EMISSION FROM A CRYSTAL WITH A STATIC DOMAIN

The data presented here suggest a simple interpretation of the behavior of the intensity of the spontaneous emission

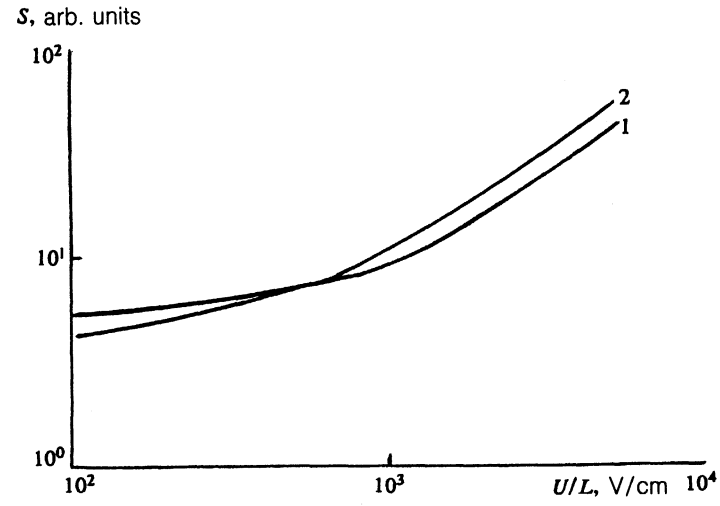


FIG. 3. Intensity of the spontaneous emission, $S$, versus the average field in the sample at various pressures $P$, kbar: *1*—4.5; *2*—6.7.

as a function of the voltage and of the pressure in strong electric fields. Figure 3 shows the intensity of the spontaneous emission detected by a germanium-gallium detector (with a sensitivity band of 80–120 $\mu$m) as a function of the applied voltage at various values of $P$. Beginning at about 4 kbar, the intensity increases linearly with the voltage in strong fields. The beginning of this linear region corresponds at all pressures to the field outside the domain, whose value is shown in Fig. 2. With further increase in $U$, it is primarily the domain which radiates. The field in this domain is constant; the intensity increases because of the increase in the length of the domain in proportion to the voltage. Since the fields outside and inside the domain do not vary with the voltage, the total emission intensity can be written in the form

$$S \propto S_d d + S_0(L-d) = d(S_d - S_0) + S_0 L, \qquad (3)$$

where $S_d$ and $S_0$ are the specific emission intensities corresponding to uniform fields $E_d$ and $E_0$. Substituting $d$ from (2) into the latter relation, and recognizing that $E_d \gg E_0$ and thus $S_d \gg S_0$, we have at high voltages

$$S \propto S_d U/E_d L.$$

In a previous study[1] we attributed the intensification of the spontaneous emission with the pressure which was observed at a fixed (sufficiently high) voltage, to an additional buildup of holes in the heavy subband by a streaming of heavy holes. However, the data of the present study show that this growth also results from the formation of a domain. Specifically, the intensification of the spontaneous emission begins at the same threshold pressure at which the domain forms. As can be seen from (3), the total emission intensity is the sum of the intensity of the emission from the domain, which increases with the pressure because of the increase in $d$, and the intensity of the emission from the region outside the domain, where the field decreases. Since $E_d \gg E_0$ and thus $S_d \gg S_0$, the observed increase in the signal is due primarily to the increase in $d$.

This conclusion is supported by emission measurements using a photodetector sensitive in a different spectral region. Figure 4 shows the pressure dependence of the spontaneous-emission intensity at various fixed values of the applied voltage, as measured by a boron-doped silicon detector. This detector is sensitive to radiation with a photon energy above 45 meV. This energy is higher than the maximum energy gap between the valence subbands at $k=0$ in these experiments. Although the Ge⟨Ga⟩ and Si⟨B⟩ detectors detect radiation in different spectral ranges (the inset in Fig. 4 shows the scheme of corresponding optical transitions), the curves of the pressure dependence of the radiation intensity are qualitatively the same. The observed increase in the signal at $P > P_c$ is due to the formation and extension of a domain in both cases.

## 4. STIMULATED EMISSION AND STATIC DOMAIN. HYSTERESIS

The stimulated emission which arises at the threshold pressure[1] $P_{th}$ causes substantial changes in the characteris-

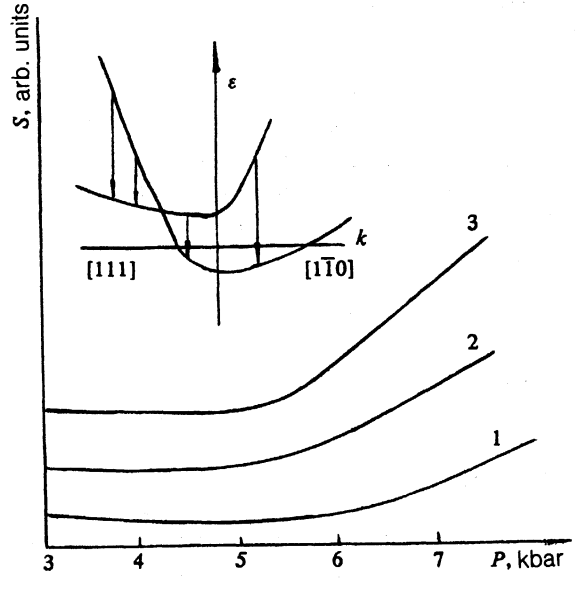


FIG. 4. Intensity of the spontaneous emission detected by the Si⟨$B$⟩ detector versus the pressure at various values of $U/L$, kV/cm: *1*—1; *2*—2; *3*—3.

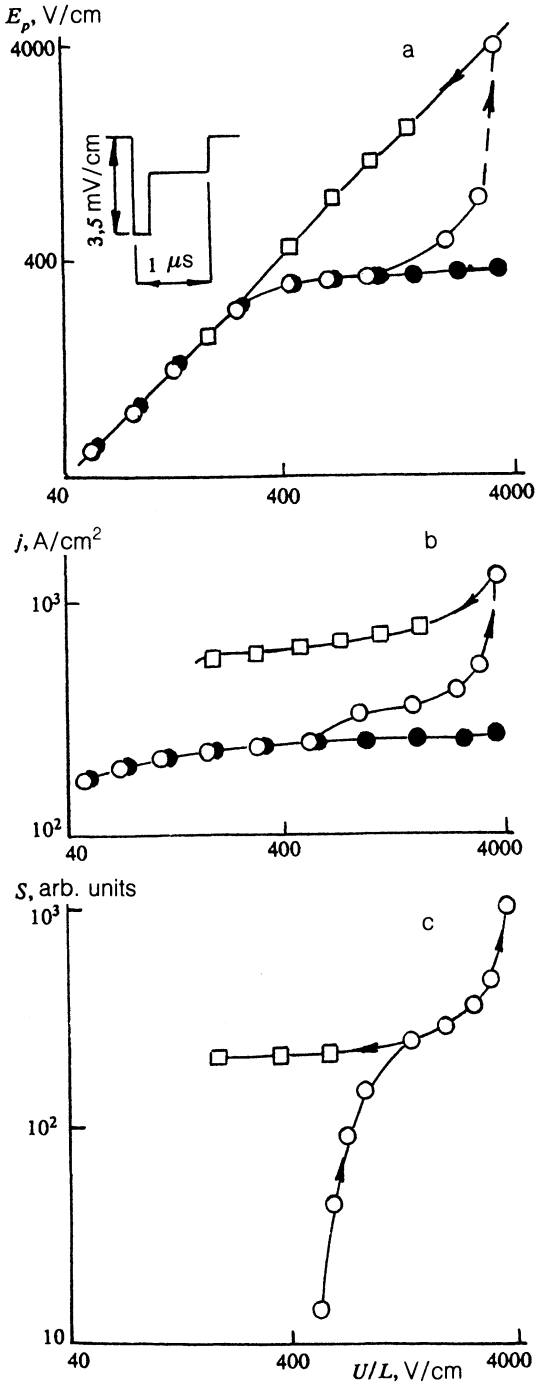


FIG. 5. Plots of (a) the probe voltage, (b) the current through the sample, and (c) the emission intensity, versus the average field in the sample at $P=9.5$ kbar. Open circles—Increasing voltage; open squares—decreasing voltage; filled circles—$E_p$ and $j$ at $P=9$ kbar ($<P_{th}$).

tics of the domain instability. Figure 5 shows the probe voltage (panel a), the current through the sample (panel b), and the emission intensity (panel c) as functions of the applied voltage at a pressure above the threshold ($P_{th}\approx 9.5$ kbar). We see from Fig. 5a that a static domain forms at $U/L\simeq 400$ V/cm, and it expands as the voltage is raised. Thereafter, if the resonance conditions hold,[1)] a stimulated emission arises (Fig. 5c). Its intensity increases sharply with the voltage. Both the current through the sample (Fig. 5b) and the voltage on the probe change. These changes show that at a sufficiently high emission intensity there are changes in the characteristic fields; i.e., the stimulated emission changes the shape of the original current-voltage characteristic of the homogeneous sample. Shown for comparison in Fig. 5, a and b, are the probe voltage and the current through the sample in the absence of stimulated emission (the filled circles) at a pressure a bit below the threshold. The current and the probe voltage reach saturation in the same voltage interval.

With further increase in the voltage (and thus in the emission intensity) we see jumps in the current and the emission. The field in the sample becomes uniform; i.e., the domain disappears. If the voltage is now reduced, the generation persists while the field remains uniform: There is sort of hysteresis. To demonstrate this effect, we used a voltage pulse with the shape shown in the inset in Fig. 5. The voltage in the short leading part of the pulse (about 0.3 μs long), sufficient to excite generation (about 3.5 kV/cm), was held constant, while the voltage over the long part of the pulse (up to 1 μs long) could be varied. The upper curves (the squares) in Fig. 5 show the changes in the voltage and the probe, in the current, and in the emission intensity as this residual voltage is reduced. We see that the generation is not cut off, and the field distribution remains uniform as the sustaining voltage is reduced substantially. In other words, two stimulated-emission regimes can exist at the same external voltage: one with a static domain and another with a uniform field. It was also possible to lower the sustaining voltage to 100 V/cm, i.e., to a point below the threshold for domain formation, without cutting off the generation. Since generation below the threshold for domain formation did not occur as the voltage was increased under these conditions, there must also be a hysteresis for stimulated emission in a uniform field. The values of the electric field for the excitation of generation and for the cutoff of generation are different.

We can thus make out the following picture of the evolution of the stimulated emission. As the voltage is raised, a static domain forms first. When this domain reaches a length sufficient for excitation of the resonator (about half the length of the sample in these experiments), stimulated emission arises.[2)] This emission in turn affects the field outside and inside the domain. When the emission becomes sufficiently intense, the domain disappears, and the generation can be sustained at a far lower applied voltage, while the field remains uniform.

## 5. STIMULATED EMISSION AND GUNN OSCILLATIONS

Figure 6 shows current-voltage characteristics of a test sample and the emission intensity in the presence of a moving Gunn domain. In the absence of stimulated emission (at $P$ just below the threshold), periodic oscillations are observed at the capacitive probe and at a small load resistance in the current circuit. These oscillations are observed over the entire voltage range used ($\gtrsim 100$ V/cm). The

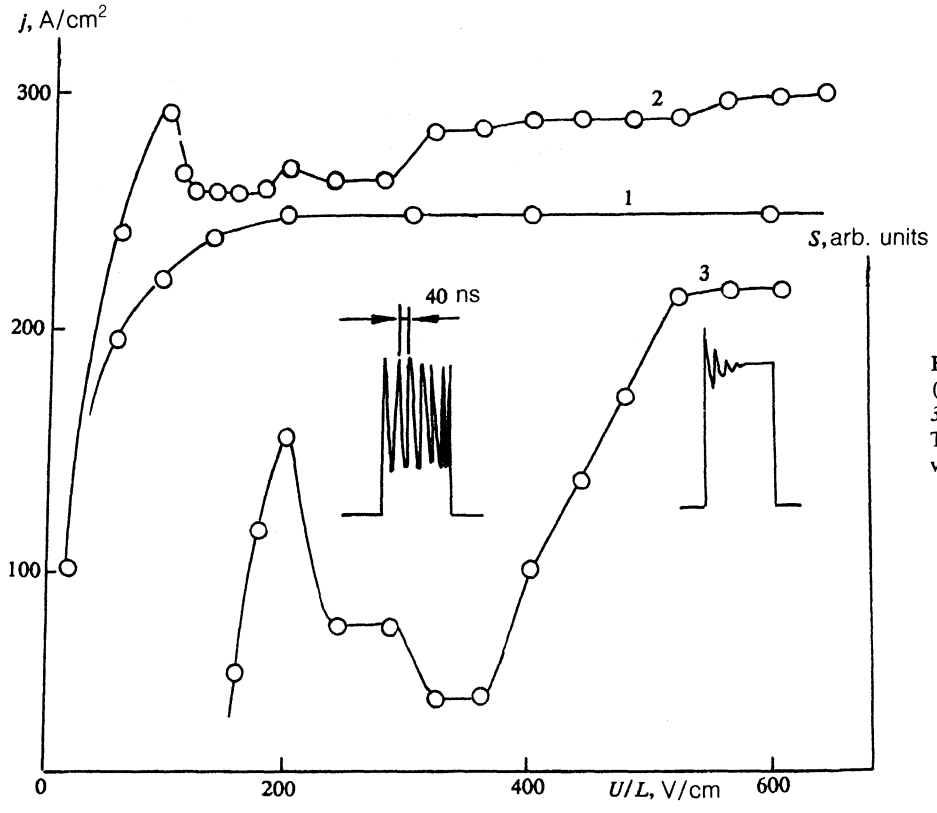


FIG. 6. *1*, *2*—Current-voltage characteristics at (*1*) $P=P_{th}-\Delta P$, $\Delta P \ll P_{th}$, and (*2*) $P=P_{th}$; *3*—emission intensity at $P=P_{th}$; ($P_{th}=9.5$ kbar). The insets show oscilloscope traces of the probe voltage.

relative amplitude of these oscillations of the probe is considerably higher than that in the current. The average current through a sample is essentially independent of the voltage (curve *1*). The oscillation period corresponds to the time it takes the domain to cross the sample at a velocity of about $10^7$ cm/s. Working from this figure and the field outside the domain, we find a hole mobility $\simeq 10^5$ cm/(V·s).

At a pressure above the threshold, and at a certain voltage (above the threshold for Gunn oscillations), stimulated emission arises. The intensity of this emission is a fairly complex function of the applied voltage (curves *2* and *3*). The reason, as in the case of a static domain, is that the intense emission changes the shape of the current-voltage characteristic of the homogeneous sample and thus the values of the field inside and outside the domain. Changes also occur in the voltage oscillations at the probe (they are shown in the insets in the corresponding voltage intervals) and in the current. These changes are in not only the amplitude but also the shape: The oscillations may become damped. Finally, at a certain voltage a further intensification of the emission cuts off the Gunn oscillations. A static domain forms near the cathode, and the current reaches saturation, exceeding the average current during the Gunn oscillations. The subsequent evolution is similar to that described above (Fig. 5): Jumps are observed in the current and the emission as a result of the destruction of the domain, and as the voltage is reduced over one pulse the emission persists, while the field remains uniform. We thus see that, at a given applied voltage, the stimulated emission can exist both in the presence of a moving domain and in a uniform field, depending on the history of events. In the case of the Gunn oscillations, the stimulated emission arises at a lower voltage than in the case of a static domain. The reason for this difference is that the field in a moving domain should be lower than that in a static domain,[6] so the moving domain reaches the critical length at a lower voltage.

## 6. STIMULATED EMISSION IN THE ABSENCE OF DOMAINS

In certain samples, apparently those whose faces are in a particularly good parallel alignment, stimulated emission arises in very weak fields, beginning at the field corresponding to impurity breakdown (curve *3* in Fig. 7). As the voltage is raised to the levels corresponding to the domain-formation fields, the emission intensifies to the extent that it prevents the formation of a domain. A domain does not appear regardless of the voltage. Current-voltage characteristics of the sample for this case, for a pressure just below the breakdown value (curve *1*) and also for $P=P_{th}$ (curve *2*), are also shown here. The onset of stimulated emission at the threshold pressure is accompanied by a jump in the current by a factor of 1.5–2. The threshold pressure for the samples is on the order of 4 kbar; i.e., it corresponds to the appearance of a region of a negative differential conductivity on the current-voltage characteristic of the homogeneous sample. No domain arises, however, since stimulated emission of higher intensity prevents the appearance of a region of a negative differential conductivity.

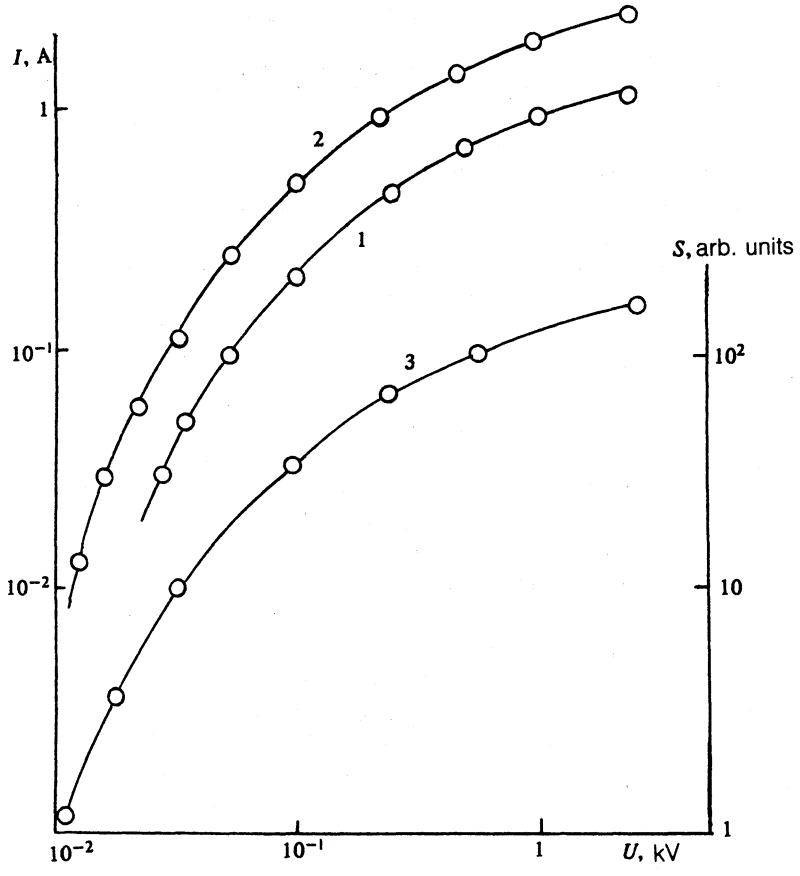


FIG. 7. *1, 2*—Current-voltage characteristics of a test sample at (*1*) $P=P_{th}-\Delta P$, $\Delta P \ll P_{th}$, and (*2*) $P=P_{th}$ ($P_{th}=4$ kbar); *3*—emission intensity.

## 7. CONCLUSION

The results presented here demonstrate that stimulated emission can arise in uniaxially deformed *p*-Ge in both the presence and absence of either a static or moving Gunn domain. Intense emission changes the shape of the current-voltage characteristic from that of the homogeneous sample and also the values of the fields inside and outside the domain. It also affects the conditions for the transition from a moving domain to a static one. The mutual effects of the stimulated emission and the characteristics of the domain instability are responsible for the fairly complex evolution of the emission intensity and of the current through the sample which is observed as the applied voltage and/or the pressure is varied. The change caused in the shape of the current-voltage characteristic by intense stimulated emission indicates that the populations of the hole subbands split by the compression change as the result of stimulated optical transitions between them. Correspondingly, the increase in the current upon the onset of stimulated emission can be explained in a natural way as resulting from an increase in the relative number of light holes involved in the conductivity. The collapse of the domain at a higher emission intensity indicates a strong suppression of the intersubband transitions of holes, with the complete disappearance of the region of negative differential conductivity. The large jump in the current (by a factor up to 10) which is observed upon appearance of stimulated emission at high voltages is a consequence of specifically the collapse of the domain and the transition of the sample to a homogeneous state. In the absence of a domain the jump in the current at the threshold pressure does not exceed a factor of 2 and is essentially independent of the voltage.

A high $Q$ of the resonator (in the case at hand, a parallel alignment of the faces) makes it possible to completely suppress the domain instability. In this case the more intense stimulated emission which arises at a pressure of about 4 kbar suppresses the region of negative differential conductivity, and domains cannot form.

We wish to thank S. Komiyama and V. I. Gavrilenko for calling our attention to the fact that the domain instability in deformed *p*-Ge can strongly affect the generation of far-IR emission. We also thank N. G. Zhdanova for a discussion of the results.

[1)] In our test samples, the resonance apparently arises because of a total internal reflection from the (long) lateral faces. These faces must be precisely parallel if generation is to occur (Ref. 1; see also Ref. 7), since a deviation from a parallel orientation would result in the loss of some of the radiation from the strong-field region.

[2)] The existence of a critical domain length for the excitation of generation resolves one experimental paradox. As the distance between the current contacts is reduced, the threshold average field $U_{th}/L$ at which the stimulated emission arises increases. Since at a high applied voltage nearly the entire voltage drop is across the domain, i.e., $U \approx E_d d$, the critical domain length $d_c$ determines the threshold voltage $U_{th} \approx E_d d_c$, which is independent of the length of the sample.

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