# OSCILLATION SHAPE OF THE HOPPING DOMAIN CURRENT DEPENDING ON THE BIAS VOLTAGE

**D. Aladashvili, Z. Adamia, A. Adamia**

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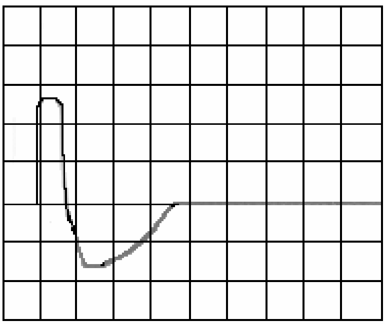
**ABSTRACT. The dependence of the shape of current oscillations observed in the hopping conductivity region in a weakly compensated *p*-Si on the supply voltage applied to the sample is established. With increasing bias voltage the current pulse shape to form a hopping domain changes significantly. The change in the shape is ascribed to voltage redistribution in corresponding regions in the bulk of the crystal.**

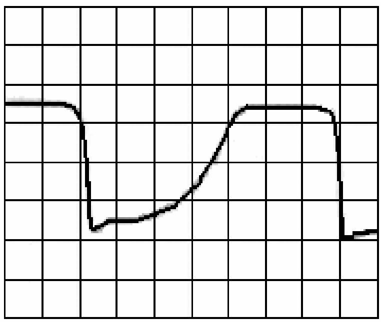
In [1] the observation of a new type of current instability in the hopping conductivity region was reported. The phenomenon manifested itself in a periodic current increase and decrease observed in the external electric circuit. The current oscillations were observed in samples with a sublinear current-voltage characteristic in the portion with a negative differential resistance. A slight decrease in the conductivity with increasing field was obtained experimentally in *p-Ge* [2]. Earlier in [3] a possibility of exponential decrease in the hopping conductivity with increasing field had been predicted. In the work a formation of dead ends in the infinite cluster (IC) of acceptors responsible both for electron trapping in high electric fields and for hopping transport was considered. The length of these ends-traps was equal to that of the characteristic grid period. A statistical current-voltage characteristic with decreasing current was computer-modeled [4] in assumption of an ideally homogeneous sample. In this case typical traps captured electrons in any part of the sample with equal probability. And the real sample always has an inhomogeneity of one kind or another. Further experimental investigations showed that current oscillations observed in the semiconductor were due to formation and motion of a hopping domain in the bulk of the sample [5]. A crystal “predisposed” to negative differential resistance passes into this state in the portion where its resistance is somewhat higher.

Precisely from this portion (cathode) the formation and motion of a volume charge similar to Gunn diode takes place [6].

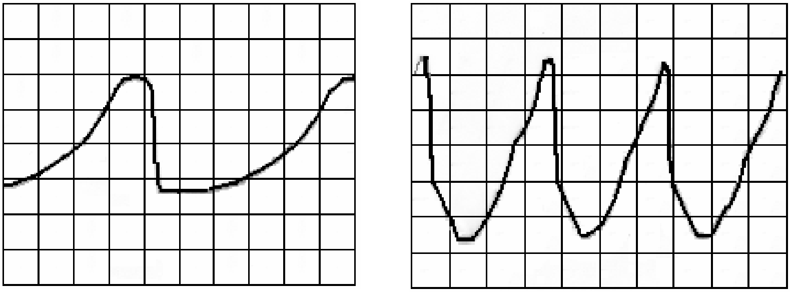
Let us consider the obtained experimental data. Current oscillations were observed in *p-Si* samples with the intrinsic impurity concentration of (5-7.5)·$10^{16}$ $cm^{-3}$ and compensation degree of (5·$10^{-3}$-4·$10^{-5}$). The generation took place at a certain critical bias voltage $U_t$. A voltage generator was switched to the sample in the pulse mode, which is necessary for synchronization of the oscillograph's work. The voltage pulse width could be controlled in the broad range. The current meter was a specially designed differential amplifier. Part of the signal was applied to the protective screen of triaxial cable from the amplifier output due to the feedback. Here capacitance leakages were neutralized thus increasing the frequency properties of the current meter. The form of the varying current signal was observed on the oscillograph and recorded on the photographic film. The process of domain formation depends on many conditions. In particular, on the type of contacts and on the conditions imposed by the external circuit.



1(*a*)



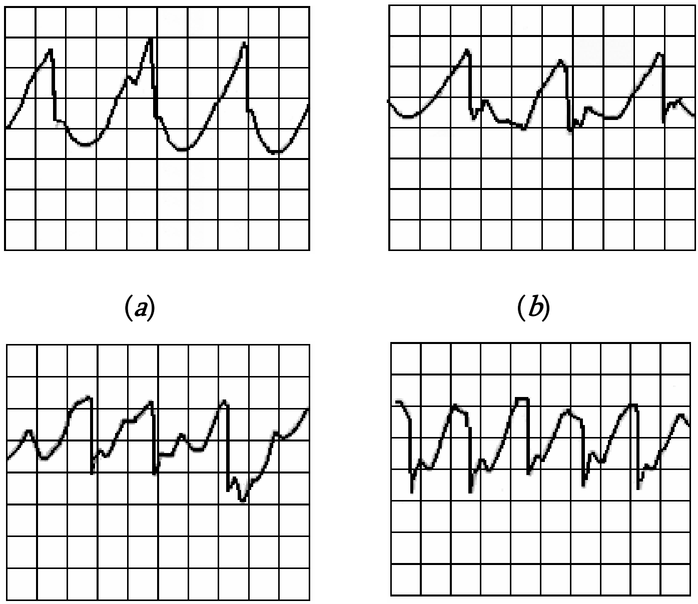
1(*b*)



1(*c*) 1(*d*)

**Fig.1.** Current pulse shape versus bias voltage $U_s$ near the threshold voltage $U_t$ of hopping domain formation. *(a)* - Trigger mode, $U_{ts}$ =31.1V, (*b*) - $U_s$ =38.4V, (*c*) - $U_s$ =39V, (*d*) - $U_s$ =40V. Scanning time *t* (horizontal scale) for (*a,b,c*) - *t* = 50 ms/part, for (*d*) - *t* = 100 ms/part. Current I (vertical scale) for (*a*) -1 nA, for (*b,c,d*) - 0.5 nA

Let us consider the change in the current pulse shape in the sample with $N_a$ = $7.3 \cdot 10^{16}$cm$^{-3}$ and $K \approx 2 \cdot 10^{-4}$ at the bias voltage $U_s$ close to the threshold of high field region formation. In this case the pulse width was 3-4 of the transit time *T*. The investigations were carried out at temperature 10K. In Fig.1, *b, c, d* a time dependence of the current shape is given for three fixed bias voltages within 38.4-41V. In this region the time-averaged current increases with increasing voltage. Here on the cathode there occurs a triangle-shaped domain moving towards the anode [7]. The formation of the next domain is preceded by a certain expectation time decreasing with the bias increase. At the bias voltage equal to the domain formation threshold the differential mobility $\mu_d$ = dv/dE = 0 (here v is the carrier drift velocity). In our case the Kroemer criterion is fulfilled [8]. Therefore when the bias field even slightly exceeds the threshold one, i.e. at a low $|\mu_d|$ the domain can be formed. And the higher is $|\mu_d|$, the quicker it is formed. At weak circuit screening the domain was formed due to various kind of interference; in this case the pulse repetition period depended on the pulse value and the accidental character of interference occurrence. In Fig.1 (curve *a*) a pulse shape of the current taken at voltages $U_{ts} < U_t$ in the trigger mode is also given. For this purpose a bias voltage of 31.1V was applied to the sample, which was much lower than the domain formation threshold. A short current pulse of about 40V formed a weak domain which disappeared quickly on the inhomogeneity without reaching the anode. Comparing the *a, s, c, d* curves it can be noticed that with an increase in bias the domain transit time rises from 150 ms (for a trigger mode) to 320 ms. It can be explained as follows.



(*a*) (*b*)

(*c*) (*d*)

**Fig.2**. Current pulse curve at high bias voltages. (*a*) - $U_s = 45$V, (*b*) - $U_s = 47$V, (*c*) - $U_s = 49$V, (*d*) - $U_s = 50$V. The scanning time (horizontal scale) – 100 ms/part. Current I (vertical scale) - 0.5 nA.

It is clear from Fig.1 that the time dependence of the current reproduces the conductivity profile in a certain scale in the region of inhomogeneities. With increasing bias the domain velocity does not change significantly. One should also take into account that the observed inhomogeneity (the relief of the lower part of the current pulse) in the sample is due to a monotonous rise in the conductivity in the portion of approaching the anode. Therefore with increasing bias a stronger domain passes a longer distance to the anode. The best-developed is the domain shown in Fig.1 (d). Knowing its velocity $V_c \approx 0.25$ cm$^{-3}$ and the size $d \approx 150$ μm, a characteristic time of its travel to the anode can be estimated $\tau_a \approx 60$ ms. It should be mentioned that this process is actually much more complex. For example, the action of the Poole-Frenkel hopping effect accompanying the domain motion should probably be taken into account [9].

With a further increase in the bias voltage in the sample a new domain may appear on the cathode simultaneously with the motion of the domain to the anode. Here the constant voltage applied to the sample is redistributed between the domain moving towards the anode and the domains being formed. At the same time the maximum value of the generating current remains unchanged. During the motion of the high field region towards the anode the voltage excess on the cathode increases for the time longer than that of a space charge formation. Therefore this voltage will form one domain in the sample. Here, taking into consideration the tendency in development of the current pulse shape, one can assume that at a high bias voltage the domain becomes wider and takes a trapezoidal shape. In our case the complex relief of the current pulse can be explained by inhomogeneities in the short path of the domain as well as by the mutual effect of the domain moving to the anode and those being formed.

Voltage pulses with the width equal to the domain transit time were also applied to the sample. The front pulse rise of the bias voltage took place for the time much shorter that the Maxwell time $\tau_{md} = \varepsilon / 4\pi q \mu_d n_0$ of formation of a volume charge (where ε is the substance permittivity, $q$ is the charge, $\mu_d$ is the differential mobility, $n_0$ is the carrier concentration). In this case the current pulse shape observed was different from that of current oscillations taken at a constant voltage, source.

In conclusion the following can be said: At the sample voltage close to the threshold of formation of current oscillations there occurs a situation when the first domain is formed. In this case conditions are created for main diode transit regimes – the quenching regime and the lagging regime similar to the transit regime of a Gunn diode. With sufficiently high bias voltage the conditions of voltage redistribution between the domain moving towards the anode and the next domain being formed on the cathode are realized. The formation of adjustable inhomogeneities in the sample makes it possible to control the current with time, which presents a practical interest in terms of creation of analogous devices working at low temperatures.

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**Tbilisi State University**

დ. ალადაშვილი, ზ. ადამია, ა. ადამია

## ნახტომისებური დომენების დენის რხევების ფორმის დამოკიდებულება წანაცვლების ძაბვის სიდიდეზე


დასკვნა

დადგენილია დენის რხევების ფორმის დამოკიდებულება ნიმუშზე მოდებულ ძაბვაზე სუსტად კომპენსირებულ $p$-Si-ის ნახტომისებურ გამტარებლობის არეში. წანაცვლების ძაბვის გაზრდით ნახტომისებური დომენის დენის რხევის ფორმა საგრძნობლად იცვლება, რაც აიხსნება ძაბვის გადანაწილებით კრისტალის მოცულობის შესაბამის არეებში.