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Isothermal measurement of current-voltage characteristics of Gunn diodes with reflection of their discontinuities and hysteresis

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Abstract. Requirements to the measuring setup are formulated, which make it possible obtaining isothermal current-voltage (I-V) characteristics of the Gunn diode with reflection of their discontinuities, region of negative differential resistance, and hysteresis. The influence of the inductance of the test pulses' source on the occurrence of self-excitation in the connecting transmission line is investigated. The maximum permissible values of the inductance of the test signal source are indicated. Operation of the measuring circuit without self-excitation was experimentally achieved in most of the region with negative differential resistance. The isothermal I-V characteristics of the Gunn diode were measured with a controlled systematic error due to the comparing the measurement result with the developed model of the I-V characteristic.

1 Introduction

Knowledge of the current-voltage (I-V) characteristic of the Gunn diode is necessary to select the operating point, determine the range of operating temperatures, and to diagnose the quality of the diodes.

The I-V characteristic of the Gunn diode has a discontinuity, hysteresis, and a region with negative differential resistance [1]. The measurement of such a I-V characteristic presents great technical difficulties in connection with two circumstances.

First, the I-V characteristic in the region before the threshold voltage is very sensitive to self-heating of the active area (i.e., it depends on the test pulse duration). In [2], the results of measurements of I-V characteristics at pulse durations from 100 ns are presented. According to our estimates (Fig. 1), at such duration of the test signal, the threshold current can decrease by more than 25% in comparison with the non-heating pulse action. As a result, the magnitude of the discontinuity in the I-V characteristic decreases several times.

Secondly, the resistance of the test signal source R_G cannot be zero during measurements. When the threshold voltage at the diode is exceeded, the diode current

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decreases (both due to the discontinuity in the I-V characteristic and due to negative differential resistance). In this case, the voltage drop at the internal resistance of the signal source decreases, and at the diode, it increases. This leads to a skipping (smoothing in the I-V characteristic) of the discontinuity and negative differential resistance region. We discussed this effect in [3] for the real internal resistance of the test signal source.

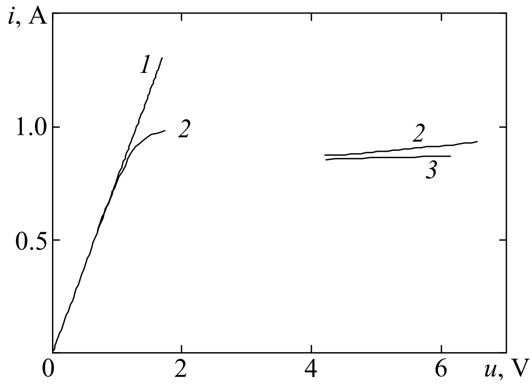

Fig. 1. I-V characteristic of the Gunn diode 3A702 at the test signal duration of 10 ns (*1*), 80 ns (*2*), and 1000 ns (*3*).

In this paper, we consider the effect of the reactive component of the internal resistance of the test signal source on the results of measurements of I-V characteristics of the Gunn diodes.

2 An example of a Gunn diode and a model of its current-voltage characteristic

Further studies were performed using the example of the Gunn diode 3A702 manufactured at JSC Scientific Research Institute of Semiconductor Devices, Tomsk.

Numerous experiments with the 3A702 Gunn diode made it possible to synthesize a model of its isothermal I-V characteristic (under non-heating pulsed action, Fig. 2). This form of the I-V characteristic of the Gunn diode is known [1], but only theoretically. We are not aware of the publications with the measurement results of such a I-V characteristic that would reflect all its aspects (discontinuity, negative differential resistance region, and hysteresis).

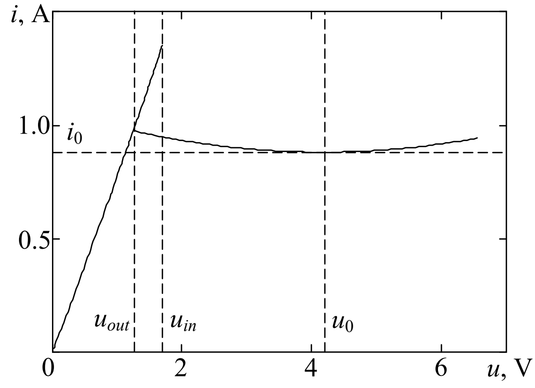

Fig. 2. The model of the I-V characteristic of the Gunn diode 3A702.

Analytically, the model of the I-V characteristic is described by the expression:

$$i(u)=\begin{cases} u/R_0 & u<u_{in} \\ -u^2/(2u_0R_d)+u/R_d+i_0-u_0/(2R_d) & u>u_{out} \end{cases}. \tag{1}$$

where R_0 is the initial resistance of the Gunn diode, R_d is the differential (negative) resistance in the domain mode at zero voltage on the diode (a virtual value), u_0 is the voltage on the diode in the domain mode, starting from which the differential resistance of the diode becomes positive, i_0 is the diode current at the voltage u_0, u_{in} is the voltage, at which the domain mode begins, when the voltage on the diode increases, and u_{out} is the voltage of the end of the domain mode, when the voltage on the diode decreases.

For the diode 3A702, the model parameters are as follows: R_0 = 1.3 Ω, R_d = −11 Ω, u_0 = 4.2 V, i_0 = 0.88 A, u_{in} = 1.7 V, and u_{out} = 1.26 V.

3 Effect of the inductance of the test pulses source on the measurement results of the I-V characteristics of Gunn diodes

As shown in [3], the internal resistance of the test pulses source when measuring the I-V characteristics of Gunn diodes should not exceed several tenths of an Ohm. Is almost impossible to realize the transmission lines with such wave impedance. When a Gunn diode is connected by a line with a large wave resistance, this line will manifest itself as a series inductance L_G.

The effect of the inductive reactance of the test signal source is basically the same as for the real resistance. When the threshold voltage is exceeded, the diode current abruptly decreases, which leads to the occurrence of a self-induction electromotive force (EMF) u_L on L_G:

$$u_L = -L_G di/dt. \tag{2}$$

At a decrease in current, the self-induction EMF turns out to be positive, which leads to an increase in the voltage on the diode and to skipping the discontinuity and negative differential resistance region in the I-V characteristic. The difference from the influence of the real resistance of the signal source is that after the end of the transient process, the voltage on the diode decreases again, the current increases, and the self-induction EMF of the opposite sign appears on L_G. This can result in switching to the sub-threshold mode. If enough energy is stored in the inductance, the process of switching between the sub-threshold mode and domain mode can take on a periodic character.

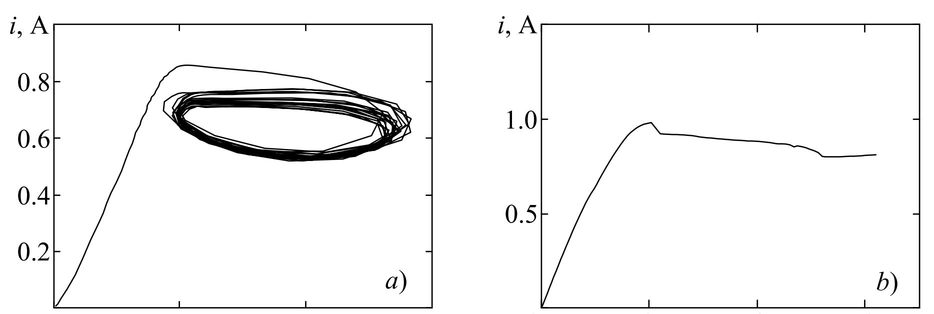

Fig. 3. Continuously recorded voltage and current on the Gunn diode 3A702 (the inductance of the connecting line is 230 nH) shown in the coordinates "voltage – current" (*a*) and the I-V characteristic measured with a low-pass filter in the presence of self-excitation of the connecting circuit (*b*).

For the example, we have continuously recorded the voltage and current on the Gunn diode 3A702 and presented them in the "voltage – current" coordinates (Fig. 3, *a*). The connecting transmission line was a twisted pair with a length of about 15 cm and an inductance of 230 nH. It is seen that due to the self-excitation, the correct measurement of the I-V characteristic in the over-threshold region is impossible.

4 Approaches to correct measurements of current-voltage characteristics of Gunn diodes in the region of discontinuity and negative differential resistance

In order to correctly display the discontinuity in the I-V characteristic, one should strive to a non-heating measurement mode. For the 3A702 diode, at a test pulse duration of 10 ns, the sub-threshold I-V characteristic is almost the same as the linear one (Fig. 1, curve *1*), which is a sign of non-heating measurement. At voltages above u_0, the distortions of I-V characteristics are also due to the self-heating of the diode, but the requirements for the pulse duration are less stringent. Curves *2* and *3* in Fig. 1 show the I-V characteristics of the 3A702 diode measured at durations of 80 and 1000 ns. The curves differ by no more than 5%. For the distortion of the I-V characteristic no more than 1%, it is sufficient to use a pulse with a duration of no more than 200 ns in this region.

The second factor of the distortion of the Gunn-diode I-V characteristic is the internal resistance of the test signal source. We obtained a source resistance of about 0.7 Ω, which is sufficient to obtain acceptable distortions of the I-V characteristic [3].

The third factor of the distortion of the I-V characteristic is self-excitation of the connecting circuit, if its impedance has an inductive nature. In principle, the self-excitation signal can be suppressed by a low-pass filter and the average voltage and current on the diode can be recorded over several periods of the self-excitation signal. This approach, however, has two drawbacks. First, such a measurement requires a lot of time, during which the active region of the Gunn diode heats up and its I-V characteristic changes. Secondly, since the transition process occurs in a nonlinear system, self-excitation is not an additive process and its filtering does not allow to correctly assess the voltage and current on the diode in the absence of self-excitation. Fig. 3, *b* shows the result of measuring the I-V characteristics of the Gunn diode using a low-pass filter. It is seen that in the self-excitation region (2.1 ... 5.2 V), the diode current is overestimated in comparison to the real one.

An obvious approach to suppressing self-excitation of the connecting circuit is to reduce its inductance. We will verify this experimentally.

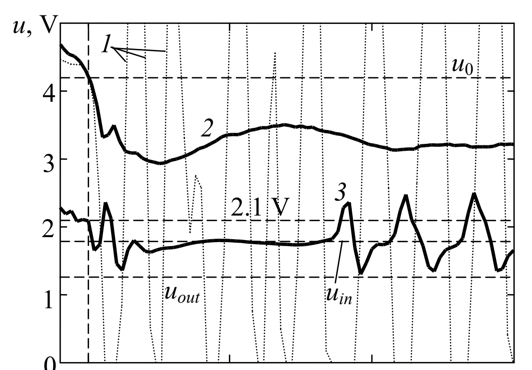

Fig. 4. Voltage on the Gunn diode 3A702: at the inductance of the measuring circuit of 230 nH (*1*) and 30 nH (*2* and *3*). (For curve *2*, the average voltage is more than 2.1 V and for curve *3*, it is less than 2.1 V).

Figure 4 shows the voltage at the Gunn diode at various inductances of the pulse source and various average voltages on the diode. It can be seen from curve *1* (the inductance of 230 nH) that self-excitation occurs immediately as soon as the voltage on the diode becomes less than u_0 (the threshold for entering the region of negative differential resistance). When the signal source inductance is 30 nH, self-excitation occurs only if the average voltage on the Gunn diode is less than 2.1 V (curve *3*). At values more than 2.1 V, the voltage on the diode assumes a steady value (curve *2*).

Now we can correctly measure the I-V characteristic of the Gunn diode over most of the region of negative differential resistance (Fig. 5, curve *1*). The measurements were performed at a pulse duration of 10 and 80 ns in the sub-threshold and over-threshold regions, respectively. The inductance of the pulse source was 30 nH. For comparison the model of I-V characteristic is shown (curve *2*). Based on a comparison of curves *1* and *2*, we can conclude that the systematic error in measuring the I-V characteristics is small.

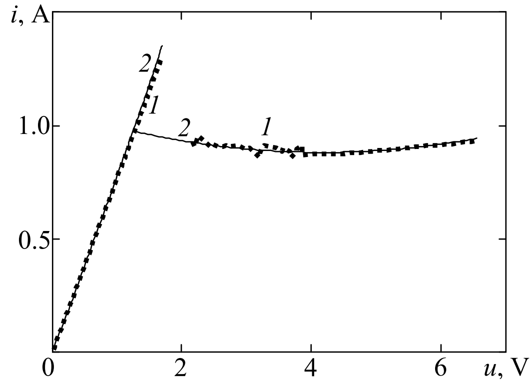

Fig. 5. Experimentally measured I-V characteristic of the Gunn diode 3A702 (*1*) in comparison with the model (*2*).

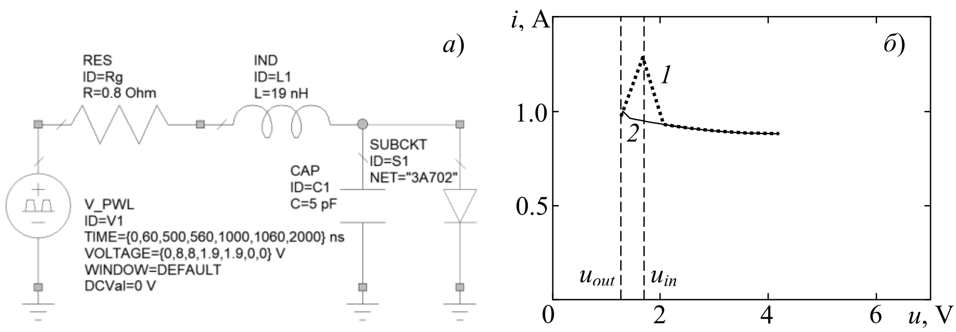

Fig. 6. The measuring circuit model in the NI AWR Design Environment (*a*) and the calculated I-V characteristic of the Gunn diode 3A702 (*b*) at inductances of the connecting circuit of 30 nH (*1*) and 19 nH (*2*).

To measure the I-V characteristic at 1.26 ... 2.1 V (domain mode), it is probably necessary to further reduce the inductance of the test signal source.

Since, to date, the inductance of a pulse source of less than 30 nH has not been experimentally implemented by us, we resorted to a computational experiment. For this, in the NI AWR Design Environment CAD system, we created a Gunn diode model in accordance with (1). Then, in CAD, the measuring circuit with the diode was assembled (Fig. 6, *a*). Additionally, the capacitance *C* of the pulse source was taken into account, since the ideal inductance under interruption of the current will give an infinite EMF. The capacitance (5 pF) was chosen so that, at the pulse source inductance of 30 nH, the boundary voltage of the self-excitation onset (2.1 V) was the same as in the experiment (Fig. 6, *b*, curve *1*). Then, we reduced the inductance of the pulse source so that self-excitation is absent starting from the minimum voltage of the domain mode (1.26 V). This occured at a source inductance of 19 nH (Fig. 6, *b*, curve *2*).

5 Conclusions

Isothermal measurement of the I-V characteristic of the Gunn diode with reflection of the I-V characteristic discontinuity and hysteresis is possible under the following conditions:

1) the duration of the test pulse in the sub-threshold region should be of the order of 10 ns or less;

2) the duration of the test pulse in the domain mode can be several hundred ns;

3) the internal resistance of the pulse source should not exceed several tenths of an Ohm;

4) the internal inductance of the pulse source must not exceed 10..20 nH (an excess inductance of the pulse source leads to the self-excitation of the connecting circuit).

As a result, we managed to measure the I-V characteristic of the Gunn diode 3A702 in the most of the range of permissible voltages.

Note that the voltage u_0 in the isothermal I-V characteristic (at which zero differential resistance is observed) is an important value from a practical point of view. For the diode voltages less than u_0, generation of the microwave signal by the diode will be distorted by the parasitic self-excitation of the diode's connecting circuit.

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