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Nonlinear Properties of an Inhomogeneous Diode Structure in a Strong Microwave Field

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Abstract

Results of experimental investigation of detection (rectification) of high power X-band microwave signal in diodes of various design (semiconductor *p-n*-junction, point-contact, Schottky, Metal-Isolator-Metal—MIM) are reported. The maximum of the detected direct voltage V vs. power P of microwave signal and subsequent polarity reversal, previously found in MIM diodes in the optical and microwave bands, have found to be characteristic of all investigated diodes as well. After the reversal of polarity, this dependence comes linear, and the sign of the voltage corresponds to thermoEMF. In some diodes, the hysteresis on $V(P)$ was observed. All 5 types of $V(P)$ of MIM diodes (have made from different pairs of metals), reported earlier, were reproduced on same *p-n*-junction diode by variable external DC bias. These results joined with abnormal frequency cutoff forced to suggest that there is an unknown mechanism for direct flow of charge carriers (and for generate direct current) in the high-frequency electrical field, which differs from the conventional rectification.

Keywords

Quadratic Detection, *p-n*-Junction, Point Contact, Schottky Barrier, High-Power Microwave Signal, Polarity Reversal, ThermoEMF, Hysteresis

1. Introduction

Rectifying (detecting) features of diodes of various designs (point-contact, *p-n*-junction, Schottky-barrier, metal-isolator-metal—MIM) for high-frequency (HF, up to the optical range) electromagnetic wave are interesting for many areas of applications: radio and optical communication, radar, information processing, and power engineering (energy harvesting and wireless power transfer systems—rectenna) [1]-[10]. For example, increasing of efficiency of rectenna at optical and infrared bands lets to use them to convert huge volume of waste heat into electricity and to reduce energy pollution of environment. Such an application of semiconductor or MIM diodes requires knowing physical processes in these structures under the electromagnetic wave of wide range of intensity (amplitude, power). Unfortunately, description of high-frequency rectifying (detecting) properties of the diodes is still based on the expansion of volt-current characteristic on powers of applied high-frequency voltage and subsequent averaging over the signal period (small-signal theory) [11] [12] [13] [14].

Same approach cannot be considered physical, since the current-voltage characteristic is a secondary property in relation to the electronic processes taking place in inhomogeneous diode structure exposed to high-frequency electromagnetic waves. Therefore, it is impossible to explain some of the experimental facts observed in various diodes at high-frequency, such as 1) a polarity reversal of the detected voltage in MIM diodes for optical [15] [16] [17] or microwave signal of high intensity [18] [19]; 2) detection of X-band signals by diodes having a cutoff frequency of 10^4 - 10^8 Hz [20]; 3) the effect of the orientation of the polarization of optical radiation on the detected voltage in planar MIM-diodes [16].

Investigating the polarity reversal of the detected voltage, Sullivan *et al.* [21] concluded that "… the final determination of the limiting response time of a diode with a metal-to-metal point contact to optical radiation frequencies and the mechanism responsible for the observed polarity reversals cannot be determined until the physical mechanism describing the operation of the diode is unambiguously established, *i.e.*, SPV, MOM, or even some other." However, we did not find similar studies on diodes of other types (point-contact, Schottky, *p-n* junction). Apparently, the problem of the origin of maximum and polarity reversal of the rectified voltage at high-power microwave signal (outside the quadratic mode) have been overshadowed due to achievements in the design and application of GaAs Schottky diodes.

In this paper, we studied experimentally the power dependence of the detected (rectified) DC open-circuit voltage $V_{oc}(P)$ or short-circuit current $I_{sc}(P)$ of diodes of various designs (point contact, *p-n*-junction, Schottky barrier) at microwave beyond the quadratic detection mode. The Experiment section describes the setup, used to measure $V_{oc}(P)$ or $I_{sc}(P)$, and the measurement process. The novelty of the results lies in the fact that the polarity reversal of the $V_{oc}(P)$ or $I_{sc}(P)$ is inherent not only in MIM diodes, but also in many other types of diodes. It is assumed that the common reason for such a complex dependence $V_{oc}(P)$ or $I_{sc}(P)$ is the inhomogeneous distribution of microwave field in the diodes.

2. Experiment

The experiments were carried out at 9.3 GHz using the setup described in **Figure 1** in standard notations for microwave technology. The M807 amplitron with a stabilized power supply served as a source of microwave oscillations, and the operating frequency was set by a movable short circuit to the maximum generated

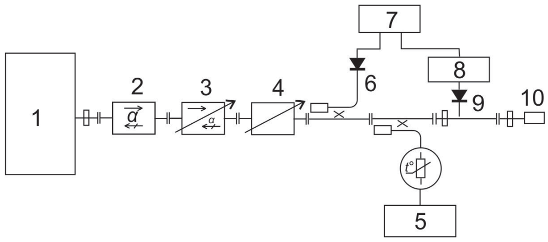


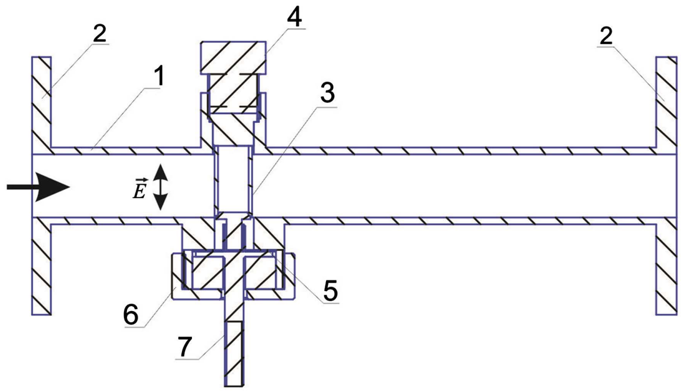
Figure 1. Setting for measuring the dependence of the detected signal on the microwave power. 1 - M807 amplitron with a stabilized power supply; 2 - ferrite valve; 3 - Faraday adjustable circulator (high-power controller); 4 - absorbing (low power) attenuator; 5 - thermistor bridge (power meter) M4 - 3 with thermistor head M5 - 20; 6 - detector diode for measuring microwave power; 7 - plotter N306; 8 - voltmeter-electrometer VK2 - 16; 9 - diode investigated in the waveguide; 10 - matched absorber.

power. The power of the microwave signal was controlled by a current controlled Faraday switch (coarse tuning for output power more than 0.1 W) and an absorbing variable attenuator (fine tuning for power less than 0.1 W). The diode under study was placed in the middle of a wide waveguide wall with a cross section of 23 × 10 mm (WR90) so the electric vector of the microwave was parallel to the diode axis (normal to the plane of the *p*-*n*-junction or oxide layer, **Figure 2(a)**). After the diode under study, a matched load was placed instead of a typical short circuit in order to exclude the influence of interference phenomena (the wave reflected from the short circuit) on the measurement results.

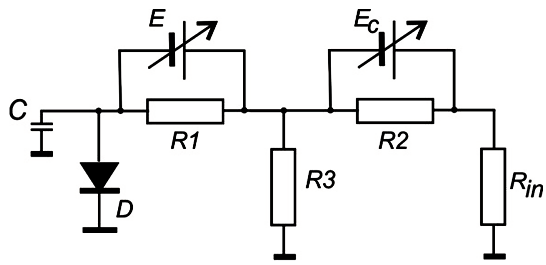
The microwave power supplied to the diode varied from μW to several W, the dependences $V_{oc}(P)$ as well as short-circuit current $I_{sc}(P)$ were recorded by N306 (H306) plotter, the inputs of which received signals from the DK-V4 (ДК-В4) detector diode (proportional to the microwave power in the waveguide), and from the output of the VK2-16 (ВК2-16) voltmeter-electrometer. The need of a VK2-16 voltmeter-electrometer (input resistance R_{in} > 100 MOhm) to measure the signal from the diode under study is due to the fact that in GA402 diodes and MIM diodes, as shown by our previous experiments [13], the open circuit mode is violated for the load resistance $R_L < 10^6$ Ohm. Note that semiconductor detectors usually operate in the short circuit (current source) mode, since their load resistance is 50 - 10^4 Ohm [15].

The circuit for supplying the initial constant bias to the diode under study when measuring the short-circuit current $I_{sc}(P)$ is shown in **Figure 2(b)**. Compensation of the initial current on the load resistor $R3$ or voltage drop on the diode was necessary in order to be able to register only detected signal against the background of a relatively high forward or reverse bias current (voltage drop).

Diodes examined were GA401 (ГА401), GA402 (ГА402), DK-s7M (ДК-с7М), DK-V4 (ДК-В4), KD514A (КД514А), D18 (Д18), tunnel GI401 (ГИ401)—all from Russia (**Table 1**, compiled from the site https://www.eandc.ru). Point-contact MIM diodes were made of W wire and Mo plate. Parameters of the diodes given in the table are taken from datasheets, and the methods for measurement these parameters are given in the book [11].



(a)



(b)

Figure 2. (a) Displacement of the investigated diode in the waveguide 23 × 10 mm. The diode is located in the middle of the wide wall of the waveguide. The axis of the diode is parallel to the electric vector of the microwave field. 1 - waveguide, 2 - flanges; 3 - diode under study; 4 - diode clampings crew; 5 - mica washer; 6 - clamping nut; 7 - output of the detected signal. (b) Circuit to supply a direct bias to the diode under study. *C* - blocking (constructive) capacitor; E, E_c - bias and compensation sources (galvanic cells with potentiometer); *R*1, *R*2 and *R*3 - resistances to supply bias, load and compensation (100 Ohm each); R_{in} - input resistance of the measuring device.

Table 1. Parameters and destination of diodes examined.

Diode type	Material and technology	flim, Hz (RC, s)	Destination
GA401 (ГА401)	Ge, diffusive *p*-*n*-junction	(2.2×10^{-12})	Parametric amplifier up to S-band
GA402 (ГА402)	Ge, diffusive *p*-*n*-junction	10^{12}	X-band parametric amplifier
DK-s7M (ДК-с7М)	Si, point-contact		X-band mixers
DK-v4 (ДК-В4)	Si, point-contact		X-band video detector
KD514A (КД514А)	Si, Schottky	(2.7×10^{-11})	Pulse diode
D18 (Д18)	Ge, point-contact	(8×10^{-8})	Pulse diode
D604 (Д604)	Si, point-contact	10^{10}	Video detector
D605 (Д605)	Si, point-contact		Detector for C- and part of X-bands (3 - 9, 4 GHz)
GI401 (ГИ401)	Ge, tunnel diode		Mixers and detectors

3. Results and Discussion

3.1. Experimental Results

Current-voltage characteristics (CVC) of industrial diodes (GA401, GA402, DK-s7M, KD514A, D18, tunnel GI401) are typical for all such diodes. CVC of MIM diodes correspond to those described in the literature [14]-[19] [21] [22] [23].

Figure 3 shows the room-temperature $V_{oc}(P)$ for these diodes. In all cases one can see the maximum of $V_{oc}(P)$, but polarity reversal was not achieved in some diodes (**Figure 3(b)** and **Figures 3(d)-(f)**) because of they are destroyed at high P. For *p-n*-junction and Schottky diodes (**Figures 3(a)-(c)**) takes place abrupt change and hysteresis in $V_{oc}(P)$.

$V_{oc}(P)$ of all diodes investigated is linear for small P. **Figure 4** shows $V_{oc}(P)$ for parametric diode GA402 and detector diode D604 for small signal as an example. It is seen that diode GA402 has a higher voltage sensitivity and linearity than the D604.

We have mentioned above that diodes as detectors of microwave and optical signals work in short-circuit mode (resistance of a load $R_L << R_i$ – intrinsic resistance of the diode as *signal source*). Dependence of short-circuit current $I_{sc}(P)$ on incident power P was measured on diodes GA402 (**Figure 5**) as the power P_0 for polarity reversal was smaller and these diodes were more stable for these investigations. It was found that the diodes can be divided into two groups according to the form of $I_{sc}(P)$ (curves 1 in **Figure 6(a)** and **Figure 6(b)**, which are similar to that of MIM-diodes in ref. [19]).

Figure 5 shows the effect of external direct bias on shape of the $I_{sc}(P)$ of diodes. Initial current and voltage drop in this experiment were compensated by circuit showed in **Figure 3**. The forward bias (curves 2 - 5 in **Figure 6(a)** and **Figure 6(b)**), reducing the potential barrier, ultimately removes the maximum $I_{sc}(P)$. The reverse bias (curves 6 - 10 in **Figure 5(a)** and **Figure 5(b)**) increases the height of the potential barrier and ultimately leads to rectification in the opposite direction. In this case, the maximum also disappears and detected signal is too small.

Previously, similar dependences $I_{sc}(P)$ were observed for point-contact MIM diodes by Kwok *et al.* [18], Pyee *et al.* [19] (**Figure 6**) at 10 GHz. Sillivan *et al.* [21] and Green *et al.* [22] [23] noted a change in the sign of the detected signal when mixing or detecting laser radiation. In the case of MIM-diodes, the shape of the $I_{sc}(P)$ depended on the metals forming the diode, *i.e.* on the height and shape of the potential barrier formed by the oxide layer. In particular, Pyee *et al.* [19] made 40 types of diodes from wire W, Cu and C, TaC filaments on a metal base from Al, Hg, Mg, Mo, Nb, Ni, Pb, Sn, Ta, W, the $I_{sc}(P)$ of which it turned out to be possible to break in 5 groups (**Figure 5**). However, we are not aware of such studies on diodes with *p-n*-junction.

Let us especially note the presence of hysteresis in the $V_{oc}(P)$ of some examples of diodes GA402 (**Figure 3(a)** and **Figure 7(a)**), GA401 (**Figure 3(b)**) and

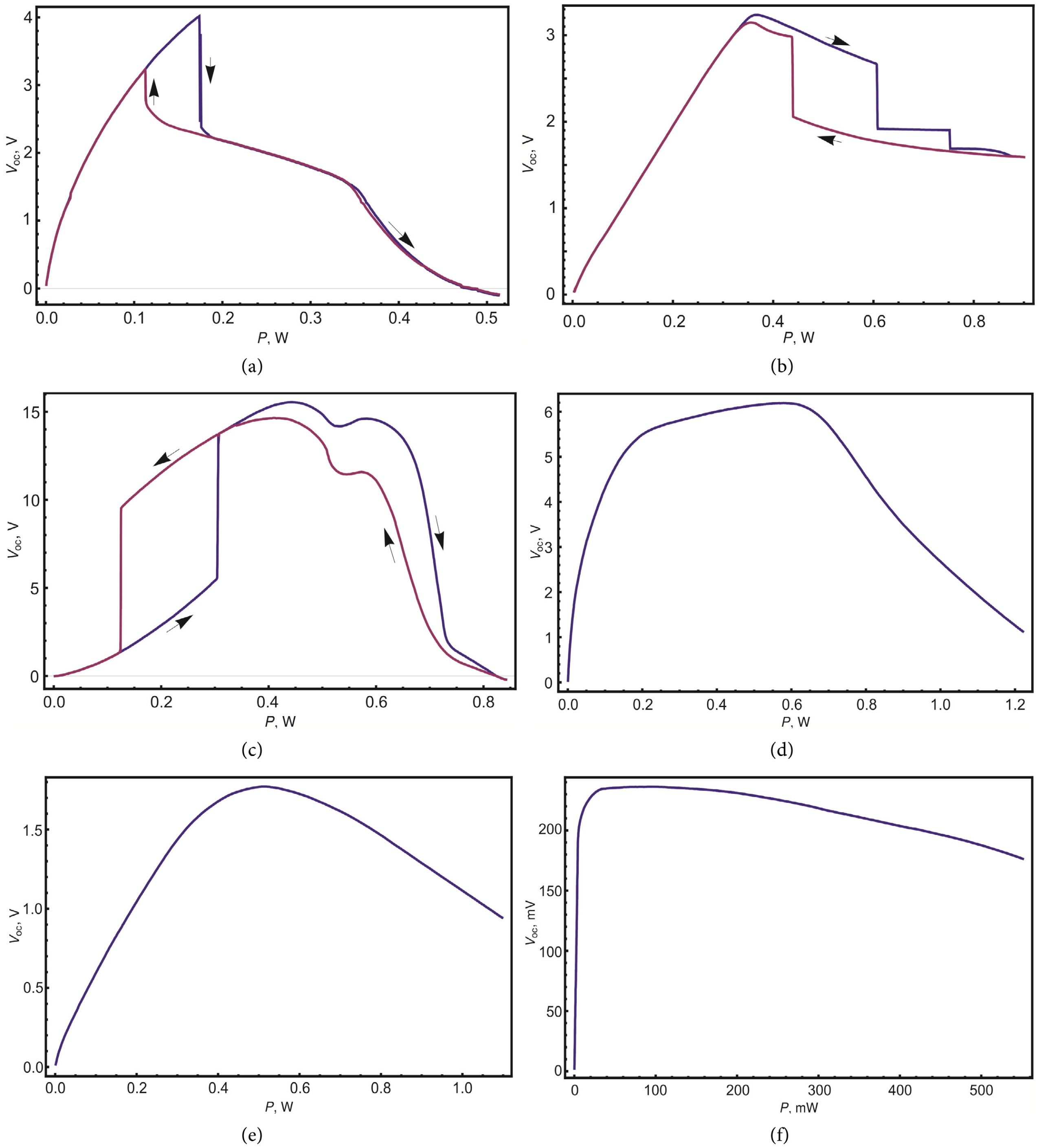


Figure 3. Power dependence of detected open-circuit voltage $V_{oc}(P)$ of diodes GA402 (a), GA401 (b), KD514 (c), DK-s7M (d), D18 (e) and GI401 (f).

KD514A (Figure 3(c)), the origin of which has not been clarified. Based on what has been said above about the role of the shape and height of the potential barrier in the detector properties of diodes, it can be assumed that this hysteresis is due precisely to the features of electronic processes in the space charge region of specific specimens of diodes.

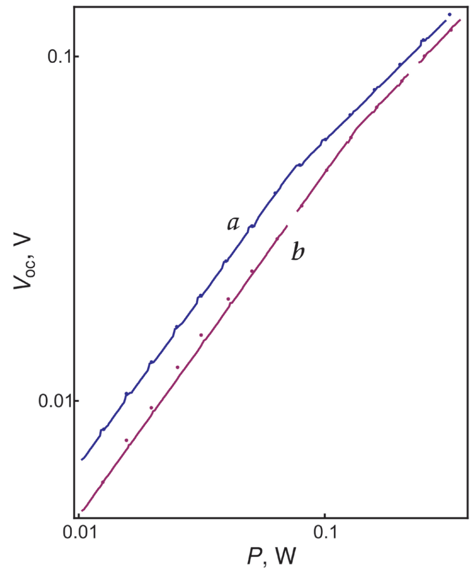


Figure 4. Small-signal detector characteristics of diodes GA402 (a) and D604 (b). Quadratic detection takes place at $P < 80$ - 120 mW.

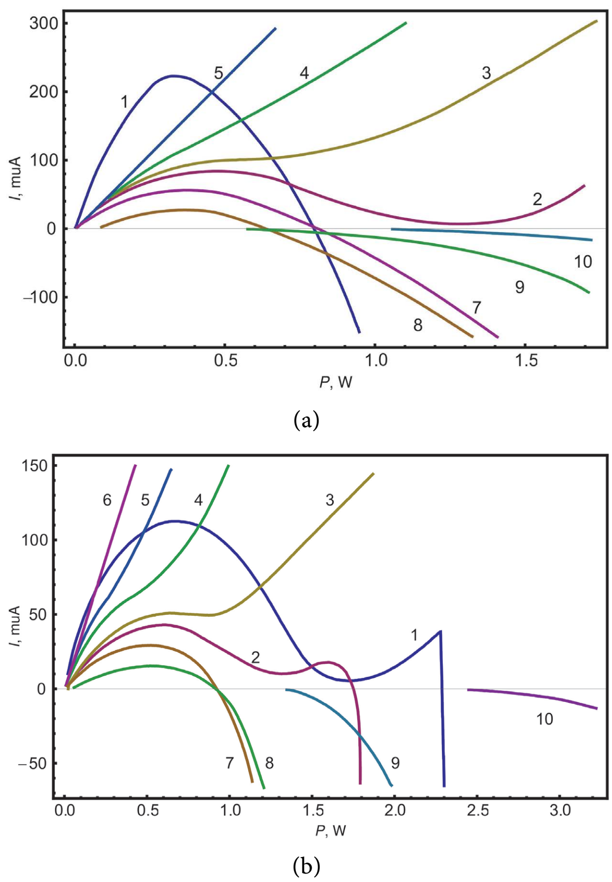


Figure 5. Effect of direct bias on microwave power dependence of short-circuit current of two group diodes GA402 (compare with **Figure 6**). (a): 1 - without a bias; forward current: 2 - 2 μA; 3 - 20 μA; 4 - 100 μA; 5 - 500 muA; reverse voltage: 6 - 0.1 V; 7 - 1 V: 8 - 3 V; 9 - 5 V; 10 - 10 V; (b): 1 - without a bias; forward current: 2 - 1 nA; 3 - 100 nA; 4 - 2 μA; 5 - 200 μA; reverse voltage: 6 - 0.2 V; 7 - 1 V: 8 - 3 V; 9 - 6 V; 10 - 10 V.

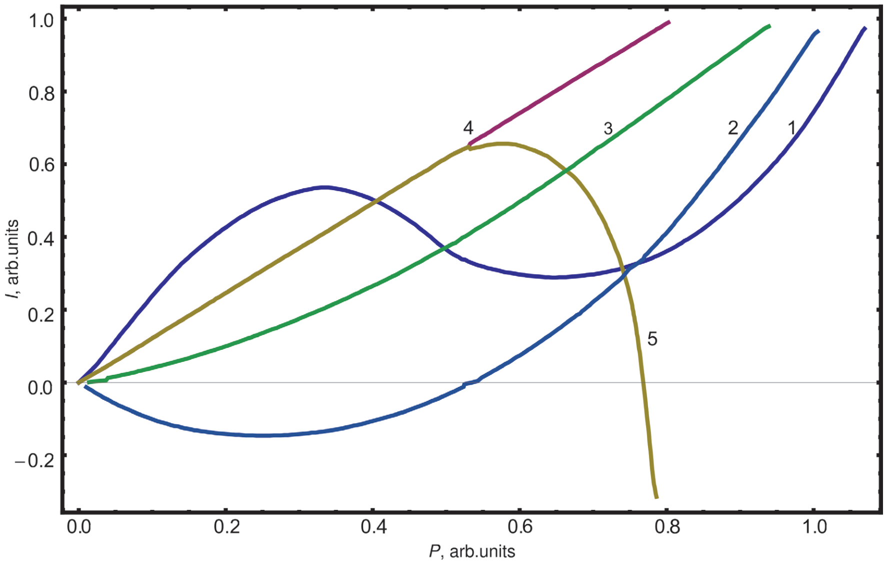
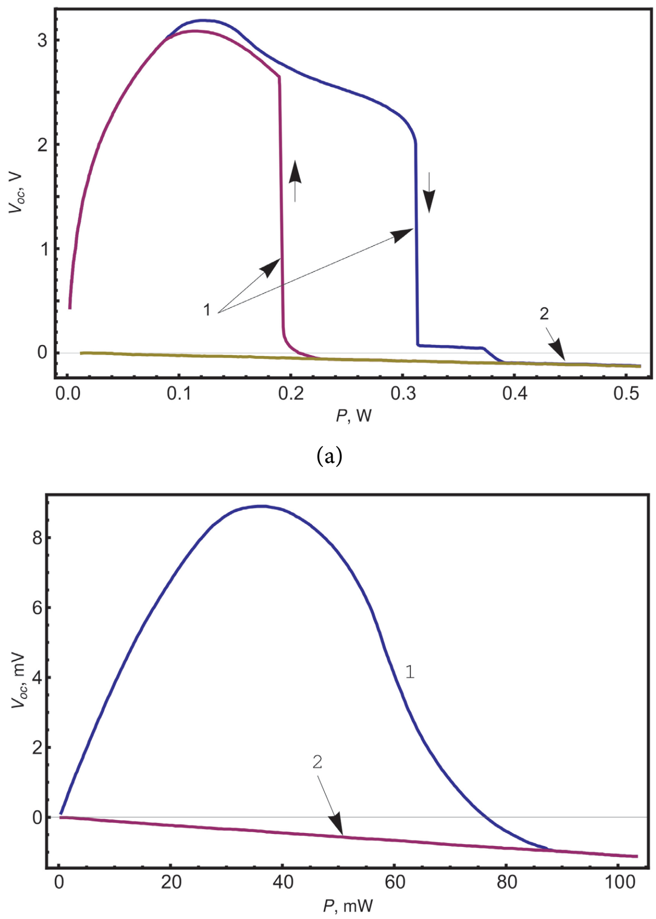


Figure 6. Detected current of MIM-diodes at microwave for various pairs of contacted metals [19]: 1 and 2 - Al + W (oxide layer on Al generated in different ways), 3 - 5 – pairs did not signed.



(a)

(b)

Figure 7. Microwave power dependence of open-circuit voltage V_{oc} of the serviceable (1) and deliberate breakdown (2) diodes GA402 (a) and MIM (W + Mo) (b).

Figure 7 shows $V_{oc}(P)$ of diodes GA402 and MIM (W-Mo) serviceable (1) and after deliberate breakdown (2). In this experiment, the opposite of the polarity of the detected signal and thermoEMF in diodes is manifested.

The opposite of the polarity of the rectified voltage and thermoEMF is also confirmed by the oscilloscope trace of the microwave pulse of 1 μs duration, detected by the diode DK-s7M (**Figure 8**). It is seen that the maximum and a sign reversal of $I_{sc}(P)$ at high microwave power are manifested a somewhat peculiarly: at first, the pulse amplitude increases as microwave power, then a dip occurs between the leading and trailing edges of the pulse. This dip comes deeper as power increases, followed by the polarity reversal of the signal in the dip, but positive teeth remain, corresponding to the rise and fall of the microwave pulse. It follows from here that the settling and decay time of the detected signal does not exceed the duration of the rise and fall of the microwave pulse, *i.e.* no more than 0.1 μs.

3.2. Discussion

Researchers often use a small-signal approach to describe high-frequency detector (rectifier) properties of semiconductor and MIM-diodes [11] [13] [15]. This approach is based on the expansion of the CVC of the diode in powers of a small high-frequency signal $V_0\cos\omega t$ ($\omega = 2\pi f$ is angular frequency), followed by averaging over the period $T = f^{-1}$ of this signal. As a result, in the first approximation, a quadratic dependence of the detected voltage on the signal amplitude V_0 or a linear dependence on the power $P \propto V_0^2$ (quadratic detection) is obtained. Further increase in P changes this dependence to $V_{oc}(P) \propto P^{1/2} \propto V_0$ (linear detection). The disadvantage of this approach is that the CVC is a secondary (derivative) characteristic of the electronic processes occurring in the diode, and therefore is not physical. As a result, it is not possible to explain, for example, the manifestation of detector properties at X-band frequencies for diodes whose cutoff frequency is 20 kHz - 100 MHz [20].

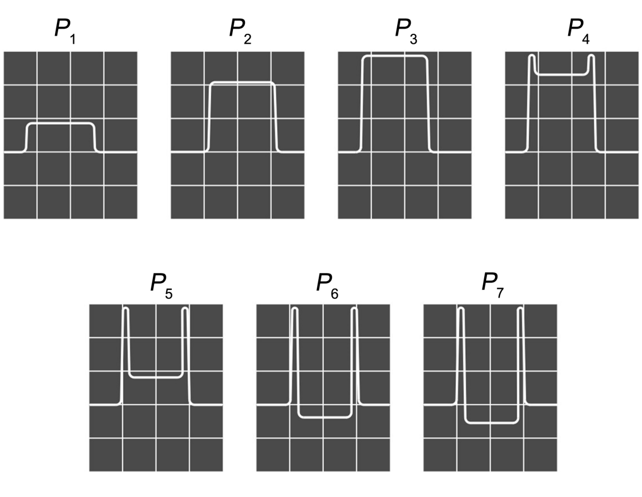


Figure 8. Oscilloscope trace of detection of pulse microwave signal in the diode DKI-1M. Vertical scale 2 V/p, horizontal scale 0.5 μs/p. $P_1 < P_2 < P_3 < P_4 < P_5 < P_6 < P_7 = 0.8$ W.

In some cases, for modeling of rectifiers performance a diode is considered to work as an ideal switch-namely, zero forward voltage, zero on-resistance, infinite off-resistance, and zero switching time [24], whereas current-voltage characteristics and switching timeof real diodesare far from this model (Figure 11.14 in ref. [13] and Figure 21 in ref. [25]).

As it is known from the Physics of semiconductor diodes [26], a direct external bias (forward or reverse) changes the height and shape of the potential barrier in the space charge region of the diode, creating an asymmetric and nonlinear current-voltage characteristic (Figure 21 in ref. [26]). Therefore, it can be argued, based on the similarity of **Figure 6** and **Figure 7** that the shape of the $V_{oc}(P)$ and $I_{sc}(P)$ are indeed related to details of the potential barrier. However, the detection (rectification) mechanisms proposed for MIM (MOM) diodes (quantum mechanical tunneling through an asymmetric barrier, enhancement of thermal field emission) [15] [16] [17] [18] [19] do not explain our experiment, since in GA402 diodes the width of the space charge region is about 1 μm, which excludes the electron tunneling.

There are old contradictory points of view in literature on the polarity of direct voltage, generated in diodes under microwave or optical radiation [26] [27] [28]. To solve the problem, we carried out additional experiments by a deliberate breakdown of all type diodes. Diodes were broken through in different ways - by passing direct current (>1A), high microwave power (more than 10 W), and in MIM diodes also by mechanical force. After the breakdown, the CVC of the diodes became linear and symmetrical, *i.e.* rectification is absent, the DC resistance of the diodes is several Ohm. These experiments showed that the polarity of the open-circuit voltage (of an operable diode) in all cases is opposite to the sign of the thermoEMF of a punched diode (**Figure 8**). The reasons for this remain to be seen. Note that the most characteristic results only are showed in **Figure 8(a)** and **Figure 8(b)** (curves 2), bearing in mind that it's similarity in all other diodes.

Most of the known studies of rectennas are devoted to the rectifying features of MIM diodes [1]-[7] [14]-[19]. Such interest in MIM diodes (mainly point-contact, as well as small area Schottky diodes) is due to a purely technical approach - the lower the resistance and capacitance of the diode, the higher the cutoff frequency. Quantum mechanical tunneling of electrons through a thin (10 - 100 nm) potential barrier, which has the simplest trapezoidal form, is considered to be the main detection mechanism of MIM-diodes. But this mechanism cannot explain polarity reversal of $V_{oc}(P)$ or $I_{sc}(P)$ at higher incident power [18] [19] [21] as well as correlation of pairs of contacting metals and shape of $I_{sc}(P)$ [19]. The mechanism of such a correlation has not been established, and it can be assumed that it is due to the properties of the potential barrier created by the dielectric (oxide) layer between the metals.

The situation forces researchers to recognize [29] that "… once stabilized, the output voltage V_{out} only depend on static parameters (i_{d0}, R, T…). In particular, it becomes independent of the geometrical capacitance. Consequently, the drastic drop of V_{out} observed in the high frequency regime cannot be induced by the diodegeometrical capacitance."

Analyses of experimental results on rectennas and rectifiers as well as theories of MIM-diode working led Zhao *et al.* [2] to conclude: "It's worth noting that there is no suitable rectifier for solar rectenna system to date. MIM diodes, including metal-oxide-metal (MOM) diodes and metal-vacuum-metal (MVM) diodes, are assumed as potential solutions, but the high impedance and low responsivity do not meet the requirements for visible and NIR rectification."

Problems caused by uncertainty of physical mechanism for generation of direct voltage or current take place also for thermoelectric and photoelectric converters [30] [31]. This makes us think that some unidentified yet physical mechanism is situated behind the reported above phenomena in diodes of various types. Due to this mechanism a spatial distribution of the charge carrier's density in diode and, as consequence, microwave or optical field distribution come uniform at high microwave power, so the rectified voltage disappears and thermoEMF comes the prevailed one. Same uniform distribution of charge carriers in a diode can be generated by initial direct forward current passing through the diode (**Figure 6**, curves 2 - 5). It may be considered that the hysteresis on the power dependence of open-circuit voltage in some types of *p*-*n*-junction diodes arises from this mechanismas well owing to peculiarities of the potential barrier of the junction.

4. Conclusions

Characteristic features—a maximum and a polarity reversal—take place on the power dependence of the direct open-circuit voltage or short-circuit current generated in semiconductor or MIM diodes illuminated by microwave or optical radiation.

It has been experimentally shown that the polarity of the detected (rectified) voltage or current at low microwave power (before polarity reversal) is opposite to the polarity of thermoEMF, while at high power (after polarity reversal) their signs are same.

The physical mechanism for detecting (rectifying) a strong microwave signal by semiconductor diodes of various types (*p*-*n* junction, point-contact, Schottky, MIM) does not correspond to the generally accepted one, based on the decomposition of the current-voltage characteristic of the diode in powers of the applied microwave voltage, followed by averaging over the oscillation period.

Some types of *p*-*n*-junction diodes have hysteresis of unknown origin on the power dependence of detected open-circuit voltage.

To elucidate the physical mechanism of microwaveor optical signal detection by diodes of various types (semiconductor or MIM), including sign reversal and hysteresis, further studies of the interaction of the microwave field and the electron-hole gas in the space charge region or contacts of the diodes are required.

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Conflicts of Interest

The authors declare no conflict of interests regarding the publication of this paper.

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