Gated Bow-Tie Diode With Selectively Doped 2DEG Active Layer for Microwave Sensing

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***Abstract*—Experimental studies of novel design microwave sensors based on selectively doped semiconductor structure of asymmetrical shape revealed that the gated bow-tie diodes are proper candidates for detection of electromagnetic radiation in millimeter wave range. Location of the gate over the active layer of the diode influences its electrical and detection properties as well as polarity of the detected voltage. Addition of the gate makes the asymmetry of the bow-tie diode's I-V characteristic more pronounced, what in turn results in higher voltage sensitivity value. If the gate is located by the wide contact, the sensitivity raises by one order of magnitude. When the gate is located at the narrow contact, the voltage sensitivity increases almost by two orders of magnitude in respect to the ungated diode.**

Keywords—voltage sensitivity, bow-tie diode, gate, thermoelectric electromotive force, hot carriers, selectively doped semiconductor structure, microwave

I. INTRODUCTION

Inevitable demand for new sensors of electromagnetic radiation in millimeter wavelength range makes them a hot topic nowadays due to possible applications in modern fields of technology such as imaging of concealed objects [1-3] and large area imaging [4-7], material homogeneity inspection [8-11], adaptive cruise control for automotive vehicles, as well as for future high-speed communication networks [12-16]. Such detectors need to keep up to high standards, i.e., to be sensitive and robust, inexpensive, fast enough [17]. The main element of an electromagnetic radiation sensor is a microwave (MW) diode, capable to register and measure the power of the MW signal. We have proposed a simple design of inexpensive MW diodes fabricated on the base of low resistivity GaAs substrate [18]. The diodes were useful for detection of continuous wave (CW) MW signals as well as for measurements of pulsed MW power in nanosecond time scale [19]. However, voltage sensitivity of the diodes was lower than expected. In order to achieve better sensing properties, we have introduced the idea to cover either narrow or wide parts of the asymmetrically shaped semiconductor structure with metal thus forming a bow-tie diode with a partial gate [20]. Operation principle of the bow-tie diode is based on non-uniform electron heating effects, which arise due to its doping profile and asymmetrical shape [21]. In this paper we present the further investigations of physical features of bow-tie diodes on the base of selectively doped GaAs/AlGaAs semiconductor structure and discuss the impact of partial gating above different regions of the two-dimensional electron gas (2DEG) channel.

II. THEORETICAL CONSIDERATIONS

Phenomenological approach of carrier heating by MW electric field in an asymmetrically bow-tie shaped nonhomogeneous semiconductor structure (Fig. 1) was used while solving current density, heat balance, heat flow density and Poisson's equations within warm electron approximation [21]. The expression of voltage sensitivity S_i at room temperature of the asymmetrical selectively doped semiconductor structure having a 2DEG and an Ohmic metal-semiconductor junction (the n^+-n junction) in the narrowest its part is derived as:

$$S_i = \frac{U_d}{P_i} = \frac{2R_{sh}\mu_0 \tan\alpha}{3d^2 \ln\dfrac{a}{d}} \frac{P}{P_i} N, \tag{1}$$

where U_d is the detected voltage over the ends of the diode; P_i notes the MW power in a waveguide; R_{sh} marks the sheet resistance of the active layer of the diode; μ_0 is the low field electron mobility; N is the frequency dependent factor; a, d and α refer to the geometrical parameters of the active layer of the MW diode (see Fig. 1). A more detailed analysis of this theoretical consideration is described in [20].

Equation (1) offers a way to increase the responsivity of the MW diode on the base of gated asymmetrically necked selectively doped structure with the n-n^+ junction. A gate placed over the 2DEG channel can vary electron density here depending on the polarity of the MW voltage induced across the diode as well as on the location of the gate. Therefore, additional voltage signal arises over the ends of the diode due to rectification of MW currents on the gated structure.

Consider the case when the detected voltage arising over the ends of the MW diode has polarity of thermo-

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electromotive force (TEMF) of hot electrons, i.e., positive potential of the detected signal is induced on the narrower part of the diode (left side in Fig. 1). In this situation, the current-voltage characteristic of the diode is quasilinear and the asymmetrical shape of the *n-n+* junction determines its asymmetry: electrical current flows in forward direction when the negative potential is applied to the narrower part of the diode. Thus, during the first half of the MW period the current flows in forward direction, and during the another half the current is reversed and its value is lower than in the forward direction. Introduction of a metal gate above the active layer of the MW diode near its wide contact (right contact in Fig. 1) creates additional non-homogeneity in the structure. When positive potential of the MW signal (forward direction, first half-period) is applied to the wide gate, the current through the diode increases and, contrary, when negative potential of the MW signal is applied to the gate, the current decreases (reverse direction, second half-period). Thus, additional rectification of MW currents on the wide-gated diode should increase its voltage sensitivity. When the gate is placed by the narrow contact of the diode (left contact in Fig. 1), negative potential of the MW signal diminishes electrical current due to decreased electron density under the narrow gate in the active region of the diode. This way, the forward current is quenched. While if positive potential is induced on the narrow gate, the electrical current increases. Therefore, the detected voltage signal resulting from rectification of MW currents on the narrow-gated diode will have polarity opposite to that of electromotive force of hot carriers in this diode. Thus, the decrease of voltage sensitivity should be expected with addition of the narrow gate as compared to the ungated diode.

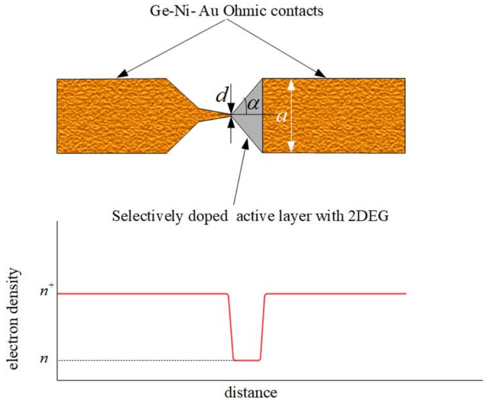


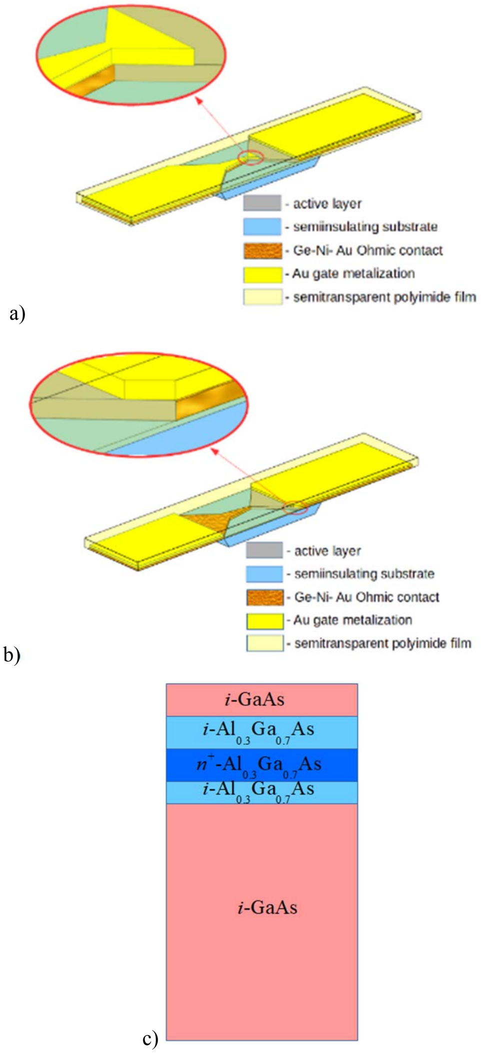
Fig. 1. Schematic view of the ungated bow-tie diode and electron density distribution in the diode.

Let us consider the case when polarity of the detected voltage corresponds to the rectification of MW currents in a metal-semiconductor junction (Schottky junction) situated in the narrowest part of the bow-tie diode. This situation can take place when Schottky junction manifests itself due to perceptible contact resistivity in the metal-semiconductor junction. Application of MW signal to the ungated bow-tie diode with expressed metal-semiconductor Schottky junction will give rise to the negative potential on the more necked part of the diode (left contact in Fig. 1).

Positive potential is induced on the narrower part of the ungated diode exposed to MW radiation. Placing narrow gate on the surface of the active layer will create additional Schottky-like junction formed between the gate and the active layer of the diode. As a result, increase of the asymmetry of current-voltage (I-V) characteristic will be followed by the voltage sensitivity rise. If the gate is placed near the wide right contact of the diode, this contact will become less Ohmic since the active layer under the gate will be depleted during the first half period of MW signal. This factor will make the I-V asymmetry weaker. Therefore, lower value of voltage sensitivity should be expected in case when the detected voltage has polarity of Schottky voltage arising over the ends of the ungated bow-tie diode.

III. SAMPLES AND EXPERIMENTAL

The semiconductor layered structure was designed on the basis of energy band diagram calculated using the Poisson equation. It was grown by means of molecular beam epitaxy (MBE) technique. Fig. 2 shows the scheme of bow-tie diodes with narrow (a) and wide (b) gates placed over the active layer of the 2DEG channel. The active layer of the bow-tie diode was composed of selectively doped GaAs/AlGaAs heterostructure epitaxialy grown onto semi-insulating GaAs substrate. Cross-sectional view of the MBE-grown structure is shown in Fig. 2 c.


a)

b)

c)

Fig. 2. Scheme of the bow-tie diode with narrow (a) and wide (b) gate placed over the active layer of the diode, and cross-sectional view of the layered semiconductor structure (c).

The pattern of asymmetrically shaped MW diodes was developed using a designed photo-resistive mask and by means of photolithography procedure. Further, 100 nm-deep mesas were created during the wet chemical etching. Ohmic contacts were formed by thermal evaporation of appropriate metals, lift-off and rapid annealing techniques. The gates were later also thermally evaporated onto the diodes. Eventually, the fabricated bow-tie diodes were transferred onto an elastic dielectric polyimide film. Fig. 3 shows the produced bow-tie diodes with narrow gate. More comprehensive description of the structure and fabrication procedure of the gated MW diodes is presented in [20].

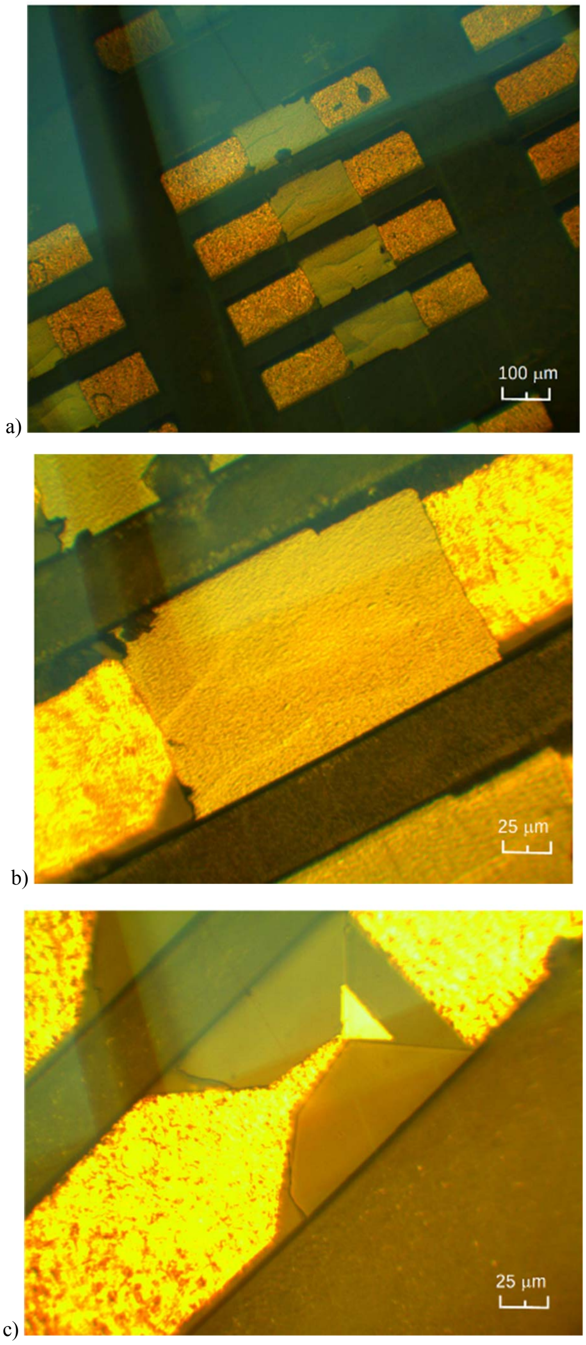


Fig. 3. (a) Patches of array of the bow–tie diodes on polyimide film; view from the side of stripped metallic contacts. View on the bow-tie diode with narrow gate from the metallic contacts' side (b) and through the polyimide film (c).

Measurements of DC I-V characteristics of the diodes were carried out using SUSS Microtech probe station EP6. Microwave detection properties were measured using Cascade Microtech high frequency probe station and a K_a frequency range sweep generator. Use of the probe station allowed to perform the investigation of the bow-tie diodes directly on the semiconductor substrate. Thus, the experiments were made in the following sequence. After the fabrication of Ohmic contacts, the I-V and voltage-power characteristics of the ungated MW diodes were achieved. Later, the gates were placed on the bow-tie diodes and DC and MW measurements were carried out again. Such sequential measurement approeach provided possibility to compare electrical parameters of particular bow-tie diode as well as to determine the influence of gating. All the measurements were performed at room temperature.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Voltage sensitivity of the ungated bow-tie diodes on the semiconductor substrate were measured at f = 30 GHz frequency. The width of the neck in the narrowest part was 1 and 2 micrometers. Subject to the value of contact resistivity of particular diode, the detected voltage had either polarity of TEMF of hot electrons or the polarity of the voltage induced across a metal-semiconductor Schottky junction (SCH). In case of the TEMF, positive potential of the detected voltage signal arose on the narrower contact of the diode (left contact in Fig. 1). When SCH voltage signal arose over the ends of the diode, opposite, negative, potential was measured on the left contact. Statistics of the voltage sensitivity of the ungated bow-tie diodes is presented in Table 1.

Almost the same number of the ungated diodes were detecting voltage signal typical of TEMF and Schottky diode polarity. For convenience, we name these corresponding diodes as TEMF and SCH, respectively. Median values of voltage sensitivity of the ungated bow-tie SCH diodes having the width of the neck 1 µm and 2 µm were 0.55 V/W and 0.4 V/W, respectively. The TEMF diodes showed practically the same median voltage sensitivity $S_{without} \approx -0.3$ V/W independent on the neck width. Positive sign of the voltage sensitivity in Table 1 is attributed to SCH diodes and negative one to the TEMFs.

When the wide and narrow gates were deposited onto the same bow-tie diodes, the measurements of voltage sensitivity were carried out again at the same frequency. The results are presented in the Table 1 as well. As it was predicted in Section II of this paper, the gates situated at different places of the bow-tie diode had different impact on the voltage sensitivity. Wide gate on the BTDWG diodes increased the sensitivity by approximately 20 times in the case of TEMF voltage. The influence of the wide gate on the SCH voltage across the BTDWG diodes is more conspicuous: the detected voltage even changed its polarity to the opposite. Addition of the narrow gate resulted in increased SCH voltage, and even caused the change of detected signal polarity, from TEMF to SCH. The overall increase of BTDNG voltage sensitivity reached two orders of magnitude.

The impact of the gates added to the bow-tie diodes is also clearly seen from their I-V characteristics. The I-V characteristic of the ungated bow-tie diode detecting SCH voltage is shown in Fig. 4, a by the blue dashed curve. Introduction of the narrow gate onto the active layer makes the asymmetry of the I-V dependence more pronounced (blue solid curve). The I-V characteristic of the ungated bow-tie diode detecting TEMF voltage is presented in Fig. 4, b (red dashed curve). The addition of the wide gate makes the I-V curve more asymmetric (red solid line in Fig. 4, b) what results in more effective rectification of MW currents and thus leads to increase of voltage sensitivity of the TEMF diodes.

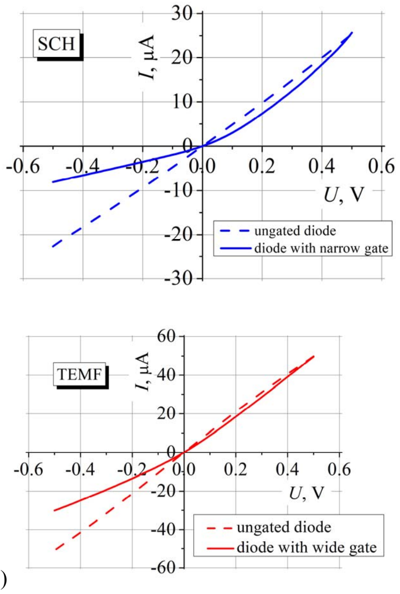
TABLE I. STATISTICS OF VOLTAGE SENSITIVITY OF THE UNGATED AND GATED BOW-TIE DIODES AT 30 GHZ. (ABBREVIATIONS BTDWG AND BTDNG MARK THE BOW-TIE DIODE WITH WIDE AND NARROW GATES, RESPECTIVELY. NUMBERS NEXT TO THE ABBREVIATIONS NOTE WIDTH OF THE NECK OF IN MICROMETERS. ABBREVIATIONS TEMF AND SCH INDICATE POLARITY OF THE DETECTED VOLTAGE, WHICH IS ASSIGNED TO THERMOELECTROMOTIVE FORCE, AND SCHOTTKY DIODE VOLTAGE, RESPECTIVELY).

Bow-tie diodes with wide gate					
Diodes	BTDWG1	BTDWG1	BTDWG2	BTDWG2	
Width of the neck d, µm	1	1	2	2	
Polarity of detected voltage	TEMF	SCH	TEMF	SCH	**Diodes without gate**
Number of diodes	34	20	28	26	
Median value of voltage sensitivity Swithout, V/W	-0.31	0.63	-0.27	0.45	
Polarity of detected voltage	TEMF	SCH	TEMF	SCH	**Diodes with gate**
Number of diodes	42	-	46	-	
Median value of voltage sensitivity Swith, V/W	-5.9	-	-5.4	-	
Swith/Swithout	19	-	20	-	
Bow-tie diodes with narrow gate					
Diodes	BTDNG1	BTDNG1	BTDNG2	BTDNG2	
Width of the neck *d*, µm	1	1	2	2	
Polarity of detected voltage	TEMF	SCH	TEMF	SCH	**Diodes without gate**
Number of diodes	15	6	12	13	
Median value of voltage sensitivity $S_{without}$, V/W	-0.29	0.48	-0.3	0.36	
Polarity of detected voltage	TEMF	SCH	TEMF	SCH	**Diodes with gate**
Number of diodes	-	22	-	22	
Median value of voltage sensitivity S_{with}, V/W	-	44.4	-	35.2	
$S_{with}/S_{without}$	-	93	-	98	

Quantitative estimation of the asymmetry of an I-V characteristics of a MW diode lets one predict its detection properties under the action of MW radiation. Such estimation was done in case of MW diode with n-n^+ junction [20]: when relaxation rate of hot electrons' energy can be neglected (what holds true at lower frequencies) and conductivity current exceeds the displacement current, the voltage sensitivity of the diode can be expressed as follows:

$$S = \frac{R_r(U) - R_f(U)}{2U}, \qquad (2)$$

where R_r and R_f stand for electrical resistance of the diode when bias voltage U is applied to the diode in reverse and forward direction, respectively. It is worth to note that estimation according to Eq. (2) gives at least tenfold increase of I-V asymmetry of the gated bow-tie diode. Therefore, respective increase of voltage sensitivity is expected in the bow-tie diodes containing the gate.



a)

b)

Fig. 4. Current-voltage characteristics of ungated and gated bow-tie diodes: (a) diode detecting the voltage of Schottky polarity (SCH), and (b) diode detecting the voltage of thermoelectric electromotive force polarity (TEMF).

Voltage-power characteristics of the gated bow-tie diodes were measured by high frequency probe station at $f = 30$ GHz frequency. Both types of diodes, TEMF and SCH, were investigated. The dependences of detected voltage on MW power are presented in Fig. 5. Usually, MW diodes are mounted in a waveguide where the diode is protected from light. However, work on a probe station enables to carry out measurements of the voltage detected on an illuminated diode. Therefore, the voltage-power characteristics presented in Fig. 5 are measured in in the dark and in case when the diode was exposed to halogen lamp.

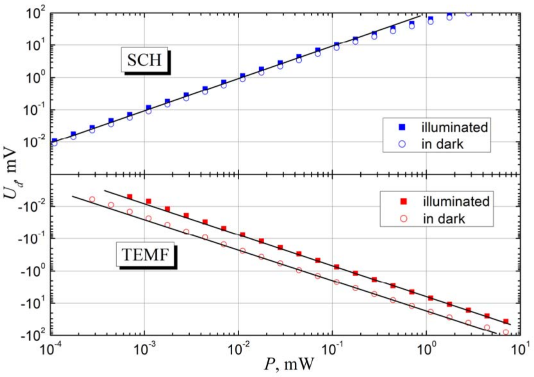


Fig. 5. Voltage-power characteristics of gated bow-tie diodes: a) diode with a narrow gate detecting the voltage of Schottky polarity (SCH); b) diode with a wide gate detecting the voltage of thermoelectric electromotive force polarity (TEMF). Open dots – in the dark, solid dots – under white light illumination.

All the characteristics are linear almost within four orders of magnitude of the MW power values for both the TEMF and SCH diodes. Voltage sensitivity of the bow-tie SCH diodes with narrow gate is higher than the sensitivity of the TEMF diode with a wide gate. The sensitivity of the SCH diode was

80 V/W when the diode was in darkness and it increased up to 100 V/W when the diode was illuminated with light. Such dependence of the voltage sensitivity on illumination can be explained by competition of two opposite mechanisms (TEMF and SCH) of MW radiation detection in the bow-tie diode. The illumination with light diminishes contribution of thermoelectromotive force component in the voltage detected by the SCH diode due to increased electron density in the active region of the diode. Therefore, slight increase of the detected voltage value of SCH polarity is observed with illumination. The impact of illumination onto the detected voltage of TEMF polarity is more expressed. The sensitivity is three times higher when the diode is shielded from the light because the sheet resistance of the diode's active region is lower. The voltage sensitivity of the bow-tie diode with n-n^+ junction increases with the increase of the sheet resistance according to Eq. (1). It is worth to note a substantial contribution of the gates to the voltage sensitivity of the bow-tie diode. The narrow gate increases the sensitivity of the SCH diode almost by two orders of magnitude, and absolute value of the sensitivity reaches hundred volts per watt. The wide gate increases the voltage sensitivity ten times for the diodes detecting the voltage of TEMF polarity reaching tens volts per watt of absolute value. Another important parameter of MW diodes is their dynamic range: the power range where the detected voltage depends linearly on MW power. The dynamic range of SCH and TEMF diodes is 30 dB and is independent on illumination as it can be seen in Fig. 5.

V. CONCLUSIONS

Asymmetrically shaped bow-tie microwave diodes on the base of selectively doped GaAs/AlGaAs semiconductor structure with gates over either narrow or wide part of the active layer were developed and investigated. In both cases, the diodes demonstrated linear voltage-power characteristics in wide dynamic range. The voltage sensitivity measurements proved presumption that sensing of the microwave signal can be improved by placing a gate over the active region of the microwave diode. In case of narrow gate, the voltage sensitivity increases by two orders of magnitude and reaches hundred V/W, while the rise by one order of magnitude can be achieved in the wide-gated diodes reaching tens V/W. Asymmetry of the I-V characteristics also increases in both cases of the gate design. Therefore, it can be concluded that partial gating over two-dimensional electron gas channel influences sensing properties of the bow-tie microwave diodes, although the narrow gate placed in the vicinity of the diode's neck is more effective in regard to the voltage sensitivity. Moreover, light illumination of the gated bow-tie microwave diode can also influence its detection properties, and this effect depends on the polarity of the detected voltage.

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