Low Frequency Noise Spectroscopy of GaN Bow-Tie THz Detectors

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***Abstract*— The low frequency (10 Hz - 20 kHz) noise characteristics of GaN-based bow-tie (BT) diodes designed for room temperature terahertz (THz) detection have been studied in the temperature range from 77 K to 320 K. Noise spectroscopy revealed the influence of the defects as charge carrier capture centers to the THz detector operation. The low frequency noise characteristics of the BT diodes are comprised from the 1/*f* and Lorentzian type spectra. The observed fluctuations are caused by charge carrier capture and release processes in the centers with (0.19-0.55) eV activation energy. The diodes with different apex width demonstrated an increase of 1/*f* type fluctuations with decrease of the apex size.**

Keywords— detector; GaN; noise; THz; trap

I. Introduction

Nowadays terahertz (THz) imaging and spectroscopy showed great prospects in a broad variety of applications and stimulated the development of THz technology [1]. Antenna coupled field effect transistors (TeraFETs), micro-bolometers, Schottky diodes have been proposed for efficient THz sensing at room temperature [2-4]. The main features for THz detectors employed in the THz imaging and spectroscopy systems are high sensitivity, low noise and short response time. Bow-tie (BT) diodes have been suggested as compact, room temperature THz detectors [5-7]. The BT diode is semiconductor layer processed in a BT shape with metalized one of its two leaves. Device operation is based on the THz wave rectification due to the non-uniform carrier heating in a trapeze-shaped semiconductor layer [5, 6]. The BT diodes have benefit of simplicity of fabrication process comparing to other THz detector concepts. Also they demonstrate very high resistance to an electrical and mechanical stress.

GaN, AlGaN and other nitride based materials are attractive wide bandgap semiconductors possessing high critical breakdown field, good thermal conductivity, large electron velocity, etc. However, lattice constant mismatch is often obtained in multilayered nitride based hetero-structures. And this leads to a higher density of defects [8]. Defects formed charge carrier trapping centers cause random carrier capture and release processes determining fluctuation of free charge carrier number in the structure. Such fluctuation is a limiting factor for the detector performance [9, 10]. It is observed that long characteristic times are characteristic for the defect's centers in the nitride based structures and carriers can be trapped in deep-level defects for a very long time [8, 9]. Therefore, instability in time of GaN-based diode operation characteristics and hysteresis behavior have been observed [8]. Also, defects play a key role on the detector's reliability and rapids its failure [10-12].

In this paper the low frequency noise was measured in order to understand physical mechanisms of the charge carrier trapping and detrapping processes and influence of those processes to the THz detector performance. Low frequency noise spectroscopy is well known method for investigation of charge carrier transport and their trapping in defects' formed centers [13-16]. Noise intensity determines the noise level of biased THz detector and its sensitivity [13, 17]. Furthermore, low frequency noise characteristic analysis reveals device quality and enables prediction of its reliability [14, 18, 19]. Thus, obtained results enable improvement of the operation characteristics of GaN-based BT detectors.

Here we present a comprehensive analysis of low frequency (10 Hz – 20 kHz) noise characteristics of GaN-based BT diodes designed for room temperature THz detection. The noise was measured to figure out an origin of the charge carriers' trapping processes, their influence to the performance and quality of the THz detector.

II. Devices and Measurement Details

The BT diodes were fabricated of $Al_{0.25}Ga_{0.75}N/AlN/GaN/SiC$ HEMT structures possessing the 2DEG density of 9×10^{12} cm^2 and the electron mobility of 1.7×10^3 cm^2/Vs and 15×10^3 cm^2/Vs at room and liquid nitrogen temperatures, respectively [20]. Ohmic contacts including one of the BT leafs metallization were fabricated of Ti/Al/Ni/Au compound annealed in nitrogen environment at 830 C. The BT diodes with different apex width: 2 μm, 5 μm, and 7 μm, are studied in this paper.

The low frequency voltage fluctuation characteristics were measured in frequency range from 10 Hz to 20 kHz. The constant current operation was guaranteed by choosing appropriate load resistance. Noise measurements were performed in a specially shielded room (Faraday cage) to avoid interferences from electrical and communication

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networks. The voltage noise spectral density was evaluated by comparing to the thermal noise of the standard resistor.

Current-voltage (resistance) characteristics were measured using semiconductor parameter analyzer Keysight Technologies B1500.

The investigation was carried out at room temperature and in the temperature range from 78 K to 320 K.

III. Results and Disscussion

Current-voltage characteristics of BT diodes are non-linear and asymmetrical (Fig. 1), what is explained by a non-uniform carriers' diffusion caused by the non-uniform electric field distribution in the trapeze-shaped semiconductor: electric field is concentrated in the vicinity of the apex [5, 6]. Also the resistance size was found to be dependent on the apex width. We noticed that investigated BT diodes demonstrated hysteresis in the resistance, which depends on the measurement cycle and the direction of voltage sweep. Also, an absolute value of the resistance varied with time. Such hysteresis and characteristics' instability with long (in order of few seconds) characteristic time show that used heterostructures contain deep defects acting as charge carrier trapping centers. Detailed experimental resistance instabilities were described in [8].

Measured voltage noise spectral density at room temperature is shown in Fig. 2. The noise was found directly proportional to voltage square at negative bias up to -2 V and at positive bias up to 0.2 V. Proportionality of the noise spectral density to voltage square indicates that observed voltage noise is determined by the resistance fluctuations. Dependence of the noise spectral density on the bias voltage polarity is caused by the same phenomena as for current-voltage characteristic. The lowest noise spectral density was observed at zero bias demonstrating optimum operation regime for BT diodes as THz detectors [5]. Noise intensity correlates with resistance of the diode: devices with larger resistance have higher noise level. Samples of lower resistance and with lower noise level over all investigated bias range demonstrate larger $1/f$ noise drop approaching to zero bias. As the resistance of the detectors with 2 μm apex width was greater comparing to the resistance of 5 μm or 7 μm apex diodes, the detectors with narrower apex also have demonstrated worse noise characteristics.

Noise spectra of the investigated BT diodes comprise from the thermal noise, $1/f$ fluctuations, and Lorentzian type components (Fig. 3). Fluctuations with the $1/f$ type spectrum usually are caused by the superposition of the charge carrier trapping and detrapping processes in defects [21]. The Lorentzian type "bumps" in the noise spectra were observed at characteristic temperature and/or bias current (Figs. 3-5). Lorentzian type "bumps" indicate presence of charge carrier trapping centers and appear, when the Fermi energy level coincides with the energy of the center: at particular operation conditions distinct charge carrier trapping centers are active.

The investigated BT diodes with larger resistance (no matters with the same or different apex width) also demonstrated larger voltage noise spectral density. Larger noise spectral density mainly is caused not by the higher intensity of the thermal noise, but by increase of the $1/f$ type fluctuations. For example, compare diodes with 7 μm and

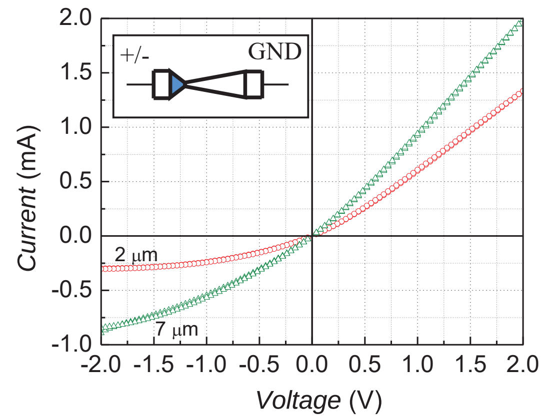

Fig. 1. Typical current-voltage characteristics of GaN-based BT diodes with 2 μm and 7 μm apex width at room temperature (inset shows electrical connection of the BT diode).

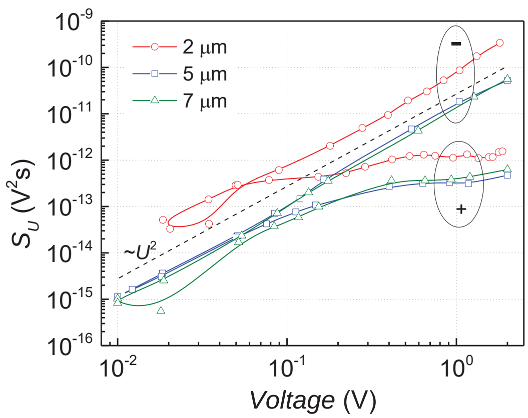

Fig. 2. Dependencies of voltage noise spectral density on voltage at room temperature of GaN-based BT diodes with different apex width: 2 μm, 5 μm, and 7 μm (curves at "+" are at the positive bias and curves at "-" are at the negative bias).

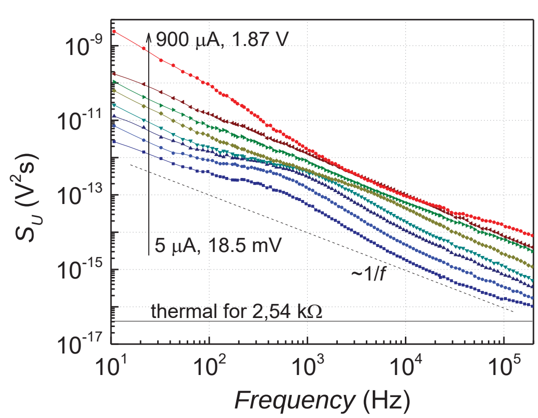

Fig. 3. Voltage noise spectra at room temperature of GaN-based BT diode with 2 μm apex at positive bias (solid line corresponds to the thermal noise at zero bias).

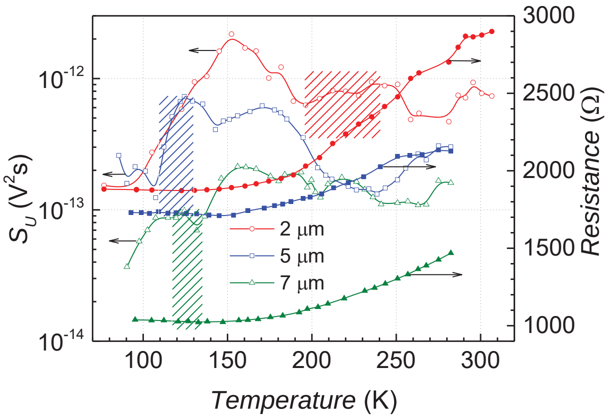

Fig. 4. Voltage noise spectral density (at 1 kHz) and resistance dependencies on temperature at positive 100 µA bias of GaN BT diodes with different apex width: 2 µm, 5 µm and 7 µm. The lined areas correspond to the temperatures where the Lorentzian-type noise spectra were observed.

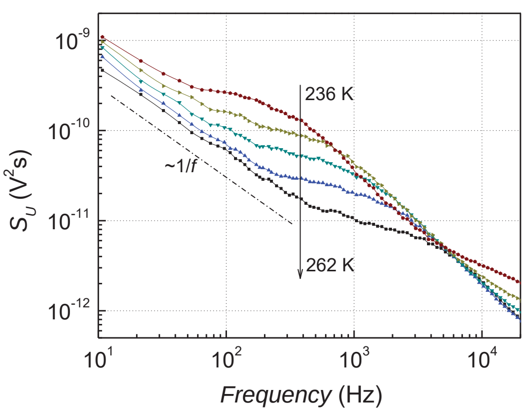

Fig. 5. Voltage noise spectra at temperature region, where the Lorentzian type spectra were observed (GaN-based BT diode with 2 µm apex at positive 100 µA bias).

2 µm apexes: resistance increase from 1.1 kΩ to 1.8 kΩ causes thermal noise increase from $1.7\cdot10^{-17}$ V^2s to $2.9\cdot10^{-17}$ V^2s (1.7 times) while measured 1/*f* noise increased from $4.1\cdot10^{-13}$ V^2s to $1.3\cdot10^{-12}$ V^2s (3.2 times) (at positive 1 V bias, noise spectral density at 1 kHz). So, larger bias causes more intensive 1/*f* type fluctuations and just minor change of the thermal noise.

Temperature characteristics of the investigated BT diodes are presented in Fig. 4. Noise spectral density rises with temperature increase at temperatures below 250 K, where resistance of the diode almost does not change. At temperature above 250 K, the noise spectral density decreases when the resistance of the device starts to increase due to the decrease of carrier mobility.

As it was mentioned, at particular temperature the Lorentzian type fluctuations were observed. The regions, where the Lorentzian type fluctuations occurred, are marked by the lined areas (see Fig. 4). An example of voltage noise

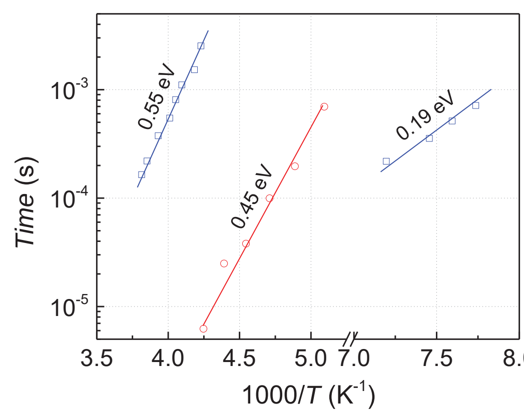

Fig. 6. Characteristic time dependencies on temperature for GaN-based BT diodes with 2 µm (red circles) and 5 µm (blue squares) apex at positive 100 µA bias (evaluated activation energies are indicated above the lines).

spectra representing activity of one trapping center is shown in Fig. 5. The Lorentzian type spectra were more evident at the positive bias than at the negative one. The observed spectra can be modeled by one or a few Lorentzians (each of them represents charge carrier trapping and detrapping process in a single center with characteristic time and activation energy), 1/*f* noise component and thermal noise base. The characteristic time of the observed trapping centers is found in the range (0.05-1) ms (see Fig. 6). Activation energies were calculated for those centers, which voltage fluctuation spectra can be approximated by a single Lorentzian type spectrum. The obtained activation energies are of 0.19 eV, 0.45 eV, and 0.55 eV (Fig. 6). The correlation between BT diode apex width and the trapping center parameters (characteristic time, activation energy) was not identified. And the influence of the defects, that also cause appearance of Lorentzian-type "bumps" in the noise spectra, is more adverse for the BT diodes with narrower apex.

IV. Conclusions

Low frequency noise characteristics of GaN-based bow-tie diodes with different apex width have been investigated in temperature range of 78-320 K. The noise spectral density dependence on bias voltage was found asymmetrical and it was similar to the asymmetrical current-voltage characteristic of the device caused by the hot carriers' diffusion under non-uniform internal electric field formed in the apex area of the trapeze-shape semiconductor.

Resistance instability in time and Lorentzian type noise spectra of the GaN-based BT diodes are explained by charge carrier trapping and detrapping processes in deep centers formed by defects. Low frequency noise spectroscopy has shown that centers have the characteristic time and the activation energy of (0.05-1) ms and (0.19-0.55) eV, respectively.

Correlation between the apex width of the investigated BT diodes and the observed trapping center parameters was not found. But influence of the defect centers was more evident in noise characteristics of the diodes with narrow apex.

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