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Peculiarities of Temperature Dependence of Detected Voltage by GaAs/$Al_{0.25}Ga_{0.75}$As Heterojunction Microwave Diode Near Interwalley Crossover

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In this paper we reveal electrical detection properties of planar MBE grown GaAs/$Al_{0.25}Ga_{0.75}$As heterojunction diode at different ambient temperatures. These investigations enabled to reveal the reasons of voltage signal rise across the heterojunction diode placed in a microwave electric field. Different temperature dependences of the detected voltage for different types of microwave diodes fabricated on the base of GaAs/$Al_{0.25}Ga_{0.75}$As heterostructures have been measured.

Keywords: semiconductor heterojunction, microwave diode, microwave detection, temperature dependence.

1. INTRODUCTION

Possibilities to grow mono-atomic semiconductor layers, that gives molecular beam epitaxy (MBE) technique, enable researchers and engineers to design materials with specific properties for various electronic devices. Microwave (MW) diodes on the base of metal-semiconductor Schottky junction are widely used as sensitive detectors of MW radiation in wide frequency range [1]. However poor electrical stability of the Schottky junction due to its surface nature stimulates search of new design of the microwave diodes.

Well known GaAs/AlGaAs heterojunction situated in bulk of semiconductor promises proper performance of microwave diode both in microwaves and infrared (IR) [2–4]. Planar design of the heterojunction diode was used for sensitive detection of MW radiation and as fast detector of IR radiation [5]. Deeper insight of electrical properties of the semiconductor heterojunction is required for better control of parameters of the detectors of electromagnetic radiation. Rectification of microwave currents [6, 7] and intervalley scattering in AlGaAs semiconductor [8] are responsible for voltage sensitivity increase in microwave diode containing GaAs/AlGaAs heterojunction.

Investigation of electrical properties of any electronic semiconductor device at different ambient temperatures is useful method for receiving additional knowledge about operation of the device. Modification of design of a device in controllable way helps to figure out the details of the device performance as well. Therefore, in this paper, we present the study of electrical properties of planar GaAs/AlGaAs heterojunction microwave diode as fabricated and these of the diode that was impacted by electric voltage pulse. Investigations were performed from room temperature down to $T = 150$ K. *I-V* characteristics of the MW diodes were measured in dc regime. Voltage power characteristics were measured at $f = 31$ GHz frequency.

2. SAMPLES

Semiconductor structure for the MW diodes was grown by MBE. Energy band structure of the *n*-GaAs/ /*n*-$Al_{0.25}Ga_{0.75}$As heterojunction is presented in Fig. 1. The band structure was calculated using Poisson simulator. The surface states at the GaAs/AlGaAs interface are ignored for the simplicity. Cross-sectional view of the MBE grown structure is shown on the picture as well. Both GaAs and AlGaAs layers are doped with $N_d = 10^{16}$ cm^{-3} donor density. The adjacent contact layers n^+-GaAs and n^+-$Al_{0.25}Ga_{0.75}$As are doped to the value of $N_d = 3 \cdot 10^{18}$ cm^{-3} donor density.

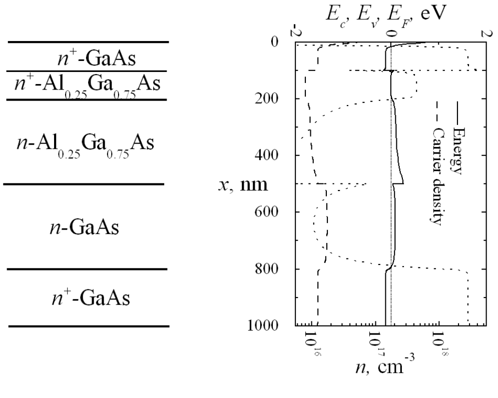

Fig. 1. Crossection of *n*-GaAs/*n*-$Al_{0.25}Ga_{0.75}$As heterojunction structure and its energy band diagram with electron density distribution

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Active region of the MW diode is a small area junction fabricated on the top of the MBE grown structure. A large area base contact of the diode was at the bottom of the MBE structure. Semiconductor mesastructure with metal contacts of the microwave diode is transferred onto a dielectric polyimide film. The heterojunction microwave diode is cut from the diode matrix and is mounted in a strip line using conductive epoxy. More detailed fabrication process of the heterojunction diode can be found in [5]. Sample 1 is the MW diode as fabricated. Sample 2 is the microwave diode properties of which (barrier height and width) is altered using 10 V pulse of milliseconds duration.

3. *I-V* CHARACTERISTICS OF THE MICRO-WAVE DIODES

Measurements of *I-V* characteristics of the diodes were performed using Agilent Semiconductor parameter analyzer. The *I-V* characteristics of Sample 1 measured at $T = 300$ K and $T = 173$ K are depicted in Fig. 2.

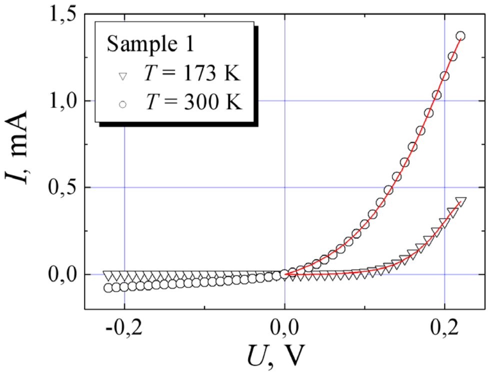

Fig. 2. *I-V* characteristics of Sample 1 measured at different temperatures (dots) and approximation of forward branches of the *I-V* characteristics using graded gap heterojunction model (lines)

Forward branches of the *I-V* characteristics are approximated using graded gap heterojunction model [9]:

$$I = I_s\left(1 - \frac{U}{\psi\eta}\right)\left[\exp\left(\frac{eU}{kT}\right) - 1\right], \tag{1}$$

where I and U denote current strength and voltage, respectively, ψ is potential barrier height, k stands for Boltzmann's constant, e notes electron charge, T is lattice temperature, η denotes potential barrier lowering factor, which is expressed as:

$$\eta = 1 - \left[\frac{2eN_d(\psi - U)}{\varepsilon}\right]^{1/2} \frac{l}{\Delta E_c}, \tag{2}$$

where N_d is donor density, ε is the dielectric constant in *n*-AlGaAs, ΔE_c stands for the conduction band discontinuity in the heterojunction, and l notes the width of the junction. Saturation current strength is expressed by the following equation:

$$I_s = \frac{eA_R TA\psi\eta}{k}\exp\left(-\frac{e\psi\eta}{kT}\right). \tag{3}$$

Here A_R notes Richardson constant, A is the area of the heterojunction. For better matching of experimental points to the theory we introduce the ideality factor n in the formula (1):

$$I = I_s\left(1 - \frac{U}{\psi\eta}\right)\left[\exp\left(\frac{eU}{nkT}\right) - 1\right]. \tag{4}$$

The best match of the theoretical curves to experimental points of the Sample 1 at room temperature is achieved when potential barrier of the junction $\psi = 0.310$ eV, the junction width $l = 8.9$ nm, and ideality factor $n = 1.65$. With temperature decrease the barrier height and ideality factor decrease and the junction width increases. At $T = 173$ K their values become $\psi = 0.287$ eV, $n = 1.34$, $l = 18.8$ nm.

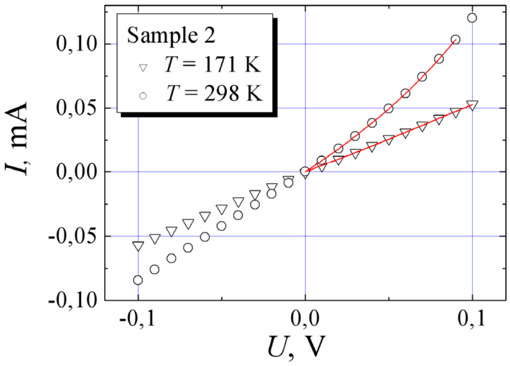

Fig. 3. *I-V* characteristics of Sample 2 measured at different temperatures (dots) and approximation of forward branches of the *I-V* characteristics using graded gap heterojunction model (lines)

The *I-V* characteristics of Sample 2 measured at $T = 298$ K and $T = 171$ K are depicted in Fig. 3. The current strength in forward direction (negative potential is applied to the upper small area contact of the diode) is also approximated by the graded-gap model. In case of MW diode with modified heterojunction (Sample 2) more pronounced temperature dependence is observed for the barrier height: it decreases from $\psi = 0.58$ eV at $T = 298$ K to the value of 0.27 eV at $T = 171$ K, while the ideality factor increases with temperature decrease: from 1.46 to 1.96. The increased junction width of the modified diode slightly increases more with temperature decrease: from 27.8 nm at $T = 298$ K to 32.5 nm at $T = 171$ K.

4. HIGH FREQUENCY PROPERTIES OF THE MICROWAVE DIODES

The polarity of detected voltage for both samples was the same in all temperature range: positive potential arise on the upper small area junction contact. However, temperature dependence was different: the detected voltage increases with temperature decrease and has a maximum at $T = 183$ K for Sample 1, while the monotonic decrease of the detected voltage was observed for the Sample 2 with temperature decrease. These experimental findings point out the different detection mechanisms in the samples.

Voltage sensitivity of the heterojunction diode due to the rectification can be calculated by formula [10]:

$$S_{rect} = \frac{R_j\gamma}{2(1 + R_s/R_j)(1 + R_s/R_j + (\omega C_j)^2 R_s R_j)}, \tag{5}$$

where $\gamma = (d^2I/dU^2)/(dI/dU)$ is curvature of *I-V* characteristic at $U = 0$, $R_j = dU/dI$ stands for the resistivity of the heterojunction at $U = 0$, R_s denotes series resistance of the diode, C_j is the barrier capacity, and ω is angular frequency of microwaves.

One more detection mechanism should take place in the heterojunction containing $Al_{0.25}Ga_{0.75}As$ layer due to the crossover of Γ, L, X valleys. The intervalley electromotive force (EMF) erases in this case. Voltage sensitivity of the heterojunction diode due to the intervalley scattering can be calculated [8]:

$$S_{\rm int} = \frac{n_0^{(1)} n_0^{(2)}}{n_0^2}(\mu^{(1)} - \mu^{(2)})\frac{\tau_{\rm int}}{(1+(\omega\tau_{\rm int})^2}\frac{K}{\pi en\mu hA}, \qquad (6)$$

where n_0 is electron density and the superscript indexes are the valley numbers, μ denotes average electron mobility, τ_{int} stands for the intervalley relaxation time, K marks the relative part of the MW power absorbed by the diode, h is the thickness of the AlGaAs layer.

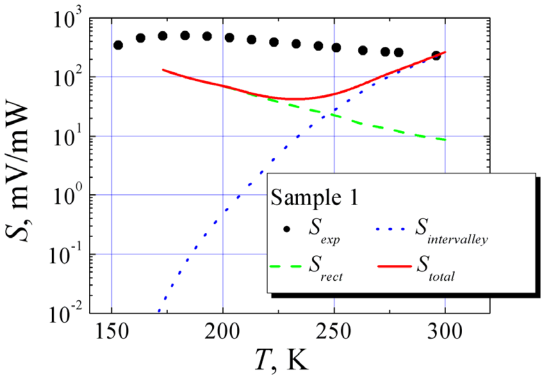

Fig. 4. Temperature dependences of voltage sensitivity of the Sample 1: dots mark experiment, dashed line is the input due to rectification of MW currents, dotted line is the input due to the intervalley emf. Solid line is the sum of dashed and dotted lines

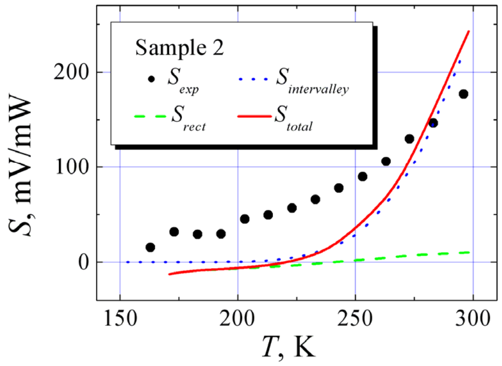

Fig. 5. Temperature dependences of voltage sensitivity of the Sample 2. Designations in the picture are the same as in Fig. 4

Temperature dependences of voltage sensitivity of as fabricated MW diode are presented in Fig. 4. Points mark the experimental data, dashed line represents the input of rectification of microwave currents in the heterojunction calculated by equation (5), and dotted line refers to the input of EMF, that was calculated using eq. (6). Solid line represents the sum of dashed and dotted lines. Temperature dependences of voltage sensitivity of the heterojunction MW diode that is impacted by electric voltage (Sample 2) are presented in Fig. 5.

Qualitative agreement between experimental points and theoretical curves accounting microwave currents rectification in $GaAs/Al_{0.25}Ga_{0.75}As$ heterojunction and intervalley electromotive force in $Al_{0.25}Ga_{0.75}As$ are observed in case of as fabricated and modified MW diode.

5. CONCLUSIONS

Temperature dependence of detected voltage in $GaAs/Al_{0.25}Ga_{0.75}As$ heterojunction can be explained by rectification of microwave currents in the junction and rise of EMF in many-valley semiconductor near the intervalley crossover. In case of pure heterojunction the rectification prevails at low temperatures, while at higher temperatures the intervalley EMF dominates. In case of electrically modified heterojunction the intervalley scattering phenomena are responsible for microwaves detection.

Acknowledgments

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REFERENCES

1. **Siegel, P. H.** Terahertz Technology *IEEE Transactions on Microwave Theory and Techniques* 50 2002: pp. 910 – 928. http://dx.doi.org/10.1109/22.989974
2. **Lechner, A., Kneidinger, M., Kuch, R.** Planar n-GaAs/N-AlGaAs Microwave Diodes *Electronics Letters* 16 1980: pp. 1 – 2. http://dx.doi.org/10.1049/el:19800001
3. **Ašmontas, S., Gradauskas, J., Kundrotas, J., Sužiedėlis, A., Šilėnas, A., Valušis, G.** Influence of Composition in GaAs/AlGaAs Heterojunction on Microwave Detection *Materials Science Forum* 297 – 298 1999: pp. 319 – 322.
4. **Ašmontas, S., Gradauskas, J., Seliuta, D., Sužiedėlis, A., Šilėnas, A., Valušis, G.** Properties of GaAs/AlGaAs Heterojunctions as Infrared Detectors *Proc. 24th Int. Conf. on the Physics of Semiconductors 24ICPS-98* D. Gershoni, Ed., 1999, World Scientific, CD-ROM (1175.pdf).
5. **Gradauskas, J., Sužiedėlis, A., Ašmontas, S., Širmulis, E., Kazlauskaitė, V., Lučun, A., Vingelis, M.** Sensitive Planar Semiconductor Detector from Microwave to Infrared Application *IEEE Sensors Journal* 10 2010: pp. 662 – 667.
6. **Sužiedėlis, A., Ašmontas, S., Kazlauskaitė, V., Gradauskas, J.** Sensitive Microwave Detector on the Basis of Hot Electrons *Electronics Letters* 45 2009: pp. 1328 – 1329.
7. **Sužiedėlis, A., Ašmontas, S., Kundrotas, J., Gradauskas, J., Čerškus, A., Nargelienė, V., Anbinderis, T.** Planar Heterojunction Diode for Millimetre Waves Detection *Proc. Progress in Electromagnetics Research Symposium (PIERS)* 2012: pp. 906 – 909.
8. **Sužiedėlis, A., Ašmontas, S., Kundrotas, J., Nargelienė, V., Gradauskas, J.** Voltage Sensitivity of Point-contact GaAs/AlGaAs Heterojunction Microwave Detector *Physica Scripta* 85 2012: pp. 1 – 5. http://dx.doi.org/10.1088/0031-8949/85/03/035702
9. **Cheung, D. T., Chiang, S. Y., Pearson, G. L.** A Simplified Model for Graded-gap Heterojunctions *Solid-State Electronics* 18 1975: pp. 263 – 266.
10. **Bahl, I., Bhartia, P.** Microwave Solid State Circuit Design. John Wiley&Sons, New Jersey, ch. 11, 2003.