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Properties of constricted 2DEG/metal structures in microwave electric fields

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Detection properties of asymmetrically constricted 2DEG/metal junctions were investigated at 10 GHz frequency at room and liquid nitrogen temperature. Operation of such detectors is based on non-uniform carrier heating in the constricted region. Different quality of the 2DEG channel was obtained for AlGaAs/GaAs modulation doped heterostructures with superlattice buffer structure and without it. Photoluminescence measurements exhibited effective charge accumulation in the AlGaAs/GaAs potential channel in the case of superlattice buffered structure, while in the non-buffered structure a substantial portion of excited carriers recombined in doped AlGaAs layer. The quality of the 2DEG channel was responsible for different polarity of the detected voltage as well as for different voltage sensitivity; in the case of the non-buffered structure the sensitivity reached almost 200 V/W value.

Keywords: 2DEG structures, microwave electric fields, microwave detector.

1. Introduction

Increasing interest in application of GHz–THz electromagnetic radiation for space telecommunications, imaging, medical and military purposes actuates the search for new sources and sensors operating in a wide frequency range [1]. Rapid progress in microelectronics during the last decades provided the possibility to reduce the dimensions of mesoscopic semiconductor structures from 3D down to 0D, thus inspiring novel investigations actual both from the fundamental and engineering points of view. For instance, two dimensional plasmon resonances are used in HEMT's for selective and broad-band detection of electromagnetic radiation [2]. We have put forward a new concept of microwave sensor containing asymmetrically shaped semiconductor structure with 2DEG layer [3].

We present the results of investigation of microwave detection properties of asymmetrically constricted 2DEG layers fabricated on the basis of modulation doped

GaAs/AlGaAs and having different underlying structure. The 3D diodes of such configuration operating on the basis of hot carrier phenomenon have shown promising detection properties from microwave up to THz region of radiation [4]. In this paper, qualitative interpretation of the experimental dependence of detected voltage polarity and magnitude on the 2DEG channel quality is presented.

2. Samples and experimental technique

Two kinds of modulation doped AlGaAs/GaAs heterostructures were grown by molecular beam epitaxy (MBE) technique on semi-insulating GaAs substrate, namely, with and without a superlattice (SL) buffer. The buffer superlattice was composed of 30 periods of undoped GaAs/$Al_{0.25}Ga_{0.75}As$ layers. In both cases, the doped n^+-$Al_{0.25}Ga_{0.75}As$ layer of 80 nm thickness was separated from undoped *i*-GaAs layer by 45 nm thick *i*-$Al_{0.25}Ga_{0.75}As$ spacer. Hall measurements revealed electron density to be 1.35×10^{12} cm^{-2} for both buffered and non-buffered structures at room temperature. At liquid nitrogen temperature the electron density increased (2.75×10^{12} cm^{-2}) in the case of non-buffered structure, and decreased (1.6×10^{11} cm^{-2}) for the structure with the SL. Electron mobility increased slightly with cooling from room down to liquid nitrogen temperature for the non-buffered structure, μ(300 K) = 2200 cm^{2}V^{-1}s^{-1} and μ(77 K) = 2600 cm^{2}V^{-1}s^{-1}, while substantial increase of the electron mobility (μ(300 K) = 2400 cm^{2}V^{-1}s^{-1} and μ(77 K) = 66000 cm^{2}V^{-1}s^{-1}) was observed in the buffered case.

The asymmetrically constricted bow-tie-like shapes of the 2DEG layer (see the inset in Fig. 2**a**) were formed by wet chemical etching of mesa structures. The etching was carried out slightly deeper than the inlying doped n^+-$Al_{0.25}Ga_{0.75}As$ layer. The width of the narrowest part, or the neck, of the constricted structure was d = 1–3 μm. Metallic contacts were fabricated by thermal evaporation of Ni/Au/Ge/Ni/Au = = 10 nm/200 nm/100 nm/70 nm/200 nm layers through photoresist mask in 3×10^{-6} torr vacuum. After rapid annealing at 430°C for 40 seconds in forming gas atmosphere, the pattern of ohmic contacts was formed by lift-off technique. The quality of ohmic contacts was controlled by transmission line method.

Photoluminescence (PL) experiments were performed under illumination of Ar ion laser (quantum energy of about 2.5 eV). The excitation intensity was varied from 0.2 up to 30 W/cm^2. The PL was registered by a cooled photomultiplier operating in photon counting regime. Microwave detection was investigated under the radiation of pulse modulated magnetron generator operating at frequency f = 10 GHz. The samples were mounted into respective rectangular waveguide, and the induced voltage was measured over the ends of the sample.

3. Experimental results and discussion

DC current-voltage (*I*-*V*) characteristics revealed quantitative correspondence between the measured electrical resistance of the buffered samples and that evaluated from their geometrical configuration. In the case of non-buffered structure the experimentally measured value of the resistance exceeded the calculated one. Moreover, the asymmetry of linear *I-V* characteristics of the buffered structure matched with the case of n–n^+ junction, where the non-metallized 2DEG part of the sample was considered as n region and the part with alloyed metal was to be treated as n^+ region. Opposite asymmetry was observed for the samples fabricated on the base of non-buffered structure: at the same voltage value the current strength was higher with positive potential applied to the metallized part of the constricted structure. DC measurements let us conclude that in this case the n and n^+ regions were counterchanged: the part of the sample with 2DEG layer had to be treated as the n^+ region, while the part with alloyed metal acted as the lightly doped n region.

Figure 1 displays PL spectra of modulation-doped GaAs/$Al_{0.25}Ga_{0.75}As$ structures at 77 K (solid circles) and 300 K (open circles) for both kinds of the samples. Two groups of peaks can be easily distinguished in the spectra. The first group of the PL lines is located between 1.7–1.9 eV. For the buffered samples, we attribute the PL peak in Fig. 1**b** to the recombination of electron–hole pairs in the $Al_{0.25}Ga_{0.75}As$ layer. The weak intensity shows that most part of the photogenerated carriers leaves this layer region and recombines in GaAs, thus emitting light quanta of lower energy. The second group of the PL lines within energies of 1.4–1.52 eV exhibits much stronger intensity, and their energetic position is very close to excitonic one in GaAs layer where the 2DEG is located. On the contrary, the peak around 1.79 eV at 77 K prevails in PL spectra of the non-buffered sample: this may be attributed to transitions from the

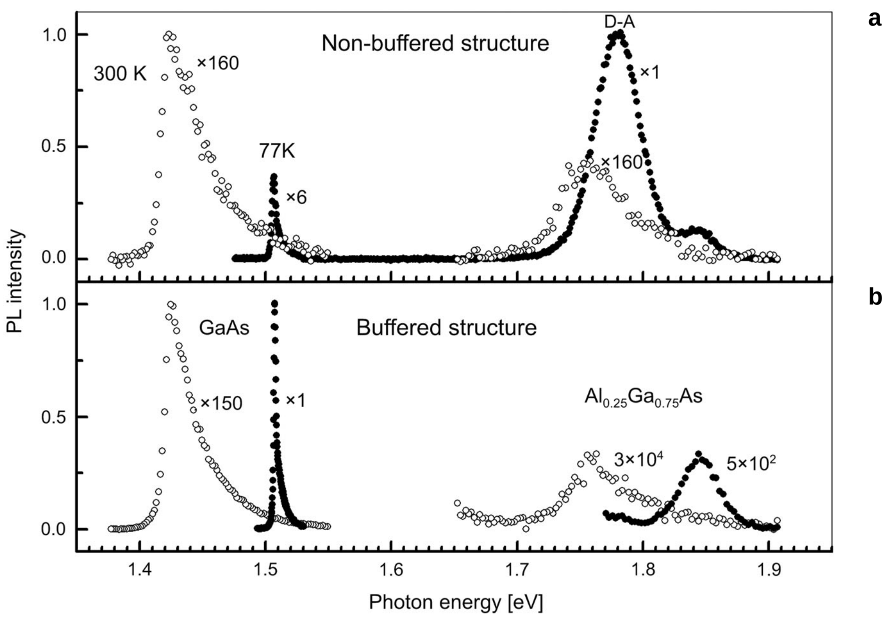

Fig. 1. PL spectra of selectively doped GaAs/$Al_{0.25}Ga_{0.75}As$ structure at 77 K (solid circles) and 300 K (open circles) for two different samples: without (**a**) and with (**b**) SL buffer layer.

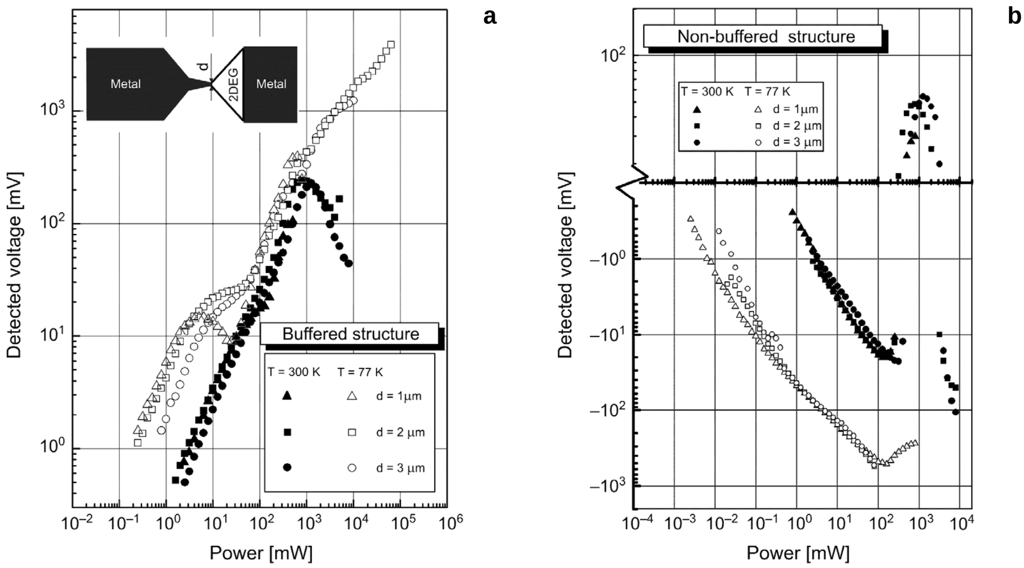

Fig. 2. Voltage power characteristics of asymmetrically shaped modulation doped structures with (**a**) and without (**b**) SL buffer measured at room (solid points) and liquid nitrogen (open points) temperatures. Inset in the graph **a**: schematic top-view of the diode.

bottom of the donor band to shallow acceptor levels: silicon in AlGaAs is known as an amphoteric impurity which can act not only as a donor but also as an acceptor [5]: the behavior of the impurity is sensitive to crystal growth conditions. At 77 K, more intensive PL in $Al_{0.25}Ga_{0.75}As$ layer than in GaAs for the non-buffered samples can be explained by dominant nonradiative recombination of electrons and holes in 2DEG region through defects and residual impurities. The PL results correlate with electron mobility data: the mobility in 2DEG structures with SL buffer is higher than in non-buffered structures.

Voltage-power characteristics of the samples with buffered and non-buffered structures are presented in Fig. 2. The polarity of the microwave-induced voltage in the case of buffered structure corresponded to that of hot carrier thermo-electromotive force arising across a semiconductor n–n^+ junction: positive potential emerged on n^+ part of the constricted structure. The sign of the detected voltage agreed with the asymmetry of the *I-V* characteristic [6]. At room temperature linear dependence of the detected voltage on power was observed up to 1 W of incident microwave radiation, while at liquid nitrogen temperature deviation from linear dependence was observed at lower values of microwave power (see Fig. 2**a**). We attribute the non-monotonic behavior of the voltage-power characteristic to hot electron transition to higher energetic valleys and to Gunn domains formation under the influence of strong microwave electric field. This phenomenon is more power-sensitive at lower temperature when the electrons with higher mobility are more sensitive to electric field strength

[7]. Voltage sensitivity was higher for the samples with a narrower neck, *i.e.*, more constricted n–n^+ junction, however this was accompanied by the more non-monotonic behavior of the characteristic due to stronger electric field in the junction. The sensitivity at 77 K was by an order higher than at room temperature since electron mobility and energy relaxation time are higher at lower temperatures.

The voltage induced across the ends of non-buffered samples was of opposite polarity (Fig. 2**b**); it corresponded to the asymmetry of the *I-V* characteristic of the sample. Linear dependence of the detected voltage on incident microwave power was observed up to 100 mW at 300 K, while at 77 K the linearity was at best maintained up to 100 μW. Nevertheless it is worthwhile to note extremely high value of voltage sensitivity at liquid nitrogen temperature: it reaches almost 200 V/W for the sample with $d = 1$ μm. Such sensitivity promises good perspectives for the application of the diodes not only to detect low intensity microwaves but even to sense THz radiation signals [4]. In this case, the opposite sign of the detected voltage such as the asymmetry of the *I-V* characteristic, can be explained as if the 2DEG channel acted as n^+ region and the part of the sample with the alloyed metal were treated as n region, *i.e.*, had lower carrier concentration.

4. Conclusions

Both DC and microwave detection properties of the constricted modulation doped diodes with 2DEG layer strongly depend on the underlying structure and on the quality of alloyed metallic contacts. When the alloyed metallic region has higher carrier concentration than the 2DEG channel, then the polarity of the detected voltage and the sign of the asymmetry of *I-V* characteristic matches the situation of nonuniform carrier heating in the 2DEG channel. When the carrier concentration of the 2DEG channel exceeds the one in the alloyed region, then the detected voltage arises due to the electron nonuniform heating in the alloyed region. The predominance of the case is influenced by the underlying buffer layer.

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