Electronic and optical properties of HEMT heterostructures with $\delta$-Si doped GaAs/AlGaAs quantum rings — quantum well system

Y D Sibirmovsky$^1$, I S Vasil’evskii$^1$, A N Vinichenko$^1$, D M Zhigunov$^2$, I S Eremin$^1$, O S Kolentsova$^1$, D A Safonov$^1$ and N I Kargin$^1$

$^1$ National Research Nuclear University ”MEPhI”, 115409, Moscow, Russia
$^2$ Lomonosov Moscow State University, 119992, Moscow, Russia

E-mail: YDSibirmovsky@mephi.ru

Abstract. Samples of $\delta$-Si doped AlGaAs/GaAs/AlGaAs HEMT heterostructures with GaAs quantum rings (QRs) on top of the quantum well (QW) were grown by molecular beam epitaxy and their properties were compared to the reference samples without QRs. The thickness of the QW was 6 – 10 nm for the samples with QRs and 20 nm for the reference samples. Photoluminescence measurements at low temperatures for all samples show at least two distinct lines in addition to the bulk GaAs line. The Hall effect and low temperature magnetotransport measurements at 4 – 320 K show that conductivity with and without illumination decreases significantly with QRs introduction, however the relative photoconductivity increases. Samples with 6 nm QW are insulating, which could be caused by the strong localization of the charge carriers in the QRs.

1. Introduction
Semiconductor quantum rings promise a wide range of applications, especially for optoelectronics, such as lasers, solar cells and photodetectors [1]. They could also be used as a low mobility layer in velocity-modulation transistors [2]. Unlike quantum dots, their conductivity can be strongly affected by magnetic field, which makes it possible to create spintronics devices without the need for magnetic materials. These cases make it necessary to study the lateral transport in the arrays of doped QRs. There are few investigations into the properties of the doped QRs. In such cases, the dopant (usually Si) is introduced directly into the QRs [1]. However, the fact that Ga and As are deposited separately during QRs growth [3] influences Si incorporation, and could even change the doping type from n to p [4]. Thus, it is prudent to investigate $\delta$-Si doped QR layers.

2. Experimental samples
In this work, electron Hall concentration and mobility, as well as PL spectra are compared for the samples with GaAs QRs-QW system surrounded by Al$_{0.3}$Ga$_{0.7}$As barrier (samples 339, 343, 344) and the reference samples without QRs (samples 320, 321 and 342) for $T = 4 – 320$ K. Special care was taken to ensure the high quality of the quantum well, which was achieved by
Figure 1. (a) QRs growth conditions and 1x1 μ AFM scans (for sample 339 a SEM scan as well); (b) layer structure of the samples, details are provided in the text.

fully reproducing a reference HEMT heterostructure until the QRs growth step. For example, electron mobility in sample 342 is $4.2 \cdot 10^5$ cm$^2$/V·s (1.65·10$^5$ cm$^2$/V·s) at $T = 4.2$ K (77 K). The dopant sheet concentration in the δ-Si layer is of the order of $10^{12}$ cm$^{-2}$ for all the samples. It is important to note that the buffer layer contains two 10 period GaAs/Al$_{0.3}$Ga$_{0.7}$As superlattices with layer thickness values of 2.4/4.7 nm and 3.5/14 nm respectively.

The QRs growth conditions, the corresponding surface scans and the layer structure of the samples are shown in Figure 1. $d_1 = 10$ nm for sample 339 and 6 nm for samples 343, 344. The top QR layer was grown for AFM measurements and was not doped. $d_2 = 3$ nm for all samples. More information is provided in Table 1. For details on the growth procedure see [5]. The spacer layer thickness is 15 nm.

Table 1. The growth conditions and resulting parameters of the QRs. $n$ is the surface density, $\lambda$ is the mean distance between the centers, $d$ is the inner ring diameter, $D$ is the outer ring diameter, $h$ is the height.

| No. | $P_{As_4}$, Torr | $T$, °C | $n$, $\mu$m$^{-2}$ | $\lambda$, nm | $d$, nm | $D$, nm | $h$, nm |
|-----|-----------------|---------|-----------------|-------------|--------|--------|--------|
| 339 | $1.5 \cdot 10^{-5}$ | 350 | 15 | 250 | 86 | 233 | 14 |
| 343 | $0.75 \cdot 10^{-5}$ | 300 | 13 | 267 | 91 | 242 | 12 |
| 344 | $0.75 \cdot 10^{-5}$ | 265 | 28 | 192 | 66 | 132 | 16 |

3. Measurement results and discussion

Electron transport was studied by Hall effect (Van der Pauw geometry) at $T = 77-320$ K and low temperature magnetotransport measurements (LTM) at $T = 2-300$ K and $B = 0-6.5$ T. The measurements were conducted for the dark and illuminated samples. Illumination for constant field Hall measurements was provided by a white LED kept at room temperature, while for LTM we used IR LED kept at the same temperature as the sample. The current was 4 μA for Hall and 6 μA for LTM.
Samples 343 and 344 are insulating which can be attributed to the decreased QW thickness and stronger localization. However, it’s possible that sample 343 was not doped due to the Si source shutter error. As for sample 344, comparing it to conducting sample 339, we can conclude that 6 nm thick QW is not enough to prevent localization of electrons inside QRs, or at least strong interface roughness scattering which starts to play a role for thin QWs [6].

Since the dopant concentrations in sample 339 and reference sample 320 are the same, we can directly compare the measurement results. Hall concentration in sample 339 has decreased by approximately $1 \cdot 10^{11}$ cm$^{-2}$ (Figure 2a), while mobility decreased more than 2 times at room temperature and around 100 times at low temperatures compared to sample 320. The main reason for both of these results is electron scattering and localization in the disordered QR layer on top of the QW. Due to low temperature of the droplet epitaxy process it is also possible that the spacer layer contains additional defects, which could trap electrons.

Figure 2. (a) Hall concentration (logarithm) for samples 339 and reference sample 320; (b) mobility for sample 339 from constant field Hall measurements ($B = 0.585$ T) and low temperature magnetotransport measurements (LTM).

Figure 3. (a) Relative photoconductivity for sample 339 and reference samples; (b) $\rho_{xx}(B)$ for sample 339 and reference sample 342.
Temperature dependence of the Hall concentration for dark and illuminated sample has the same character for samples 339 and 320. Without illumination the concentration is almost constant at low temperatures and slowly grows for $T > 150$ K, which is caused by thermal ionization of deep donors [7, 8]. For high temperatures the estimated energy is around 21 meV (Figure 2a), however using the low compensation model $n \sim \exp(-E/2kT)$ we obtain the activation energy $E = 42$ meV. Illumination at low temperatures leads to ionization of deep donors and persistent photoconductivity, the mechanism of which is described in [8, 9].

Unlike the reference samples, the mobility for sample 339 decreases as the temperature falls below 100 K, which is more common for bulk semiconductors. At low temperatures the main contributors to the scattering are the ionized shallow donors as well as extreme interface roughness caused by quantum rings. Which is why illumination of this sample leads to a significant increase in mobility, related to the screening of the potential roughness by generated electrons.

For higher temperatures, the mobility of the illuminated sample has the temperature dependence $\sim T^{-3/4}$ typical for phonon scattering. However, in the dark the dependence is weaker, which means that other significant scattering mechanisms are still involved.

Comparing concentration of photogenerated electrons (the difference between measurements with and without illumination), we can see that it’s approximately the same for samples 339 and 320. On the other hand, the relative photoconductivity (ratio of light to dark conductivity) is much higher for sample 339.

Weak Shubnikov-de-Haas oscillations were observed for sample 339 in high magnetic fields, while the reference samples show at least 4 full oscillations and quantum Hall plateaux (Figure 3b). This is expected due to low mobility (Figure 2b).

![Normalized PL spectra](image)

**Figure 4.** Normalized PL spectra for samples 339, 343, 344 and reference sample 321. Bulk GaAs line at $\sim 1.52$ eV is omitted for all samples. Labels (A) and (B) are introduced for convenience.

For PL measurements 488 nm Ar$^+$ laser was used. Attempt to identify PL lines was made by comparing their energy with GaAs band gap (1.52 eV at 20 K) and Al$_{0.3}$Ga$_{0.7}$As band gap (1.90 eV at 20 K) [10]. Bulk GaAs line was observed for all samples, as well as the line labelled (A) in Figure 4. Since line (A) exists for reference sample 321 without QRs, we have initially assumed it to be caused by the QW or the buried QW-QRs system. However, calculations indicate that
Figure 5. Temperature dependence of (a) peak energy of (A) lines and (b) normalized maximum intensity for (A) and (B) lines for all samples.

Line (A) is most likely caused by the recombination inside the buffer layer, namely the second GaAs/Al_{0.3}Ga_{0.7}As superlattice. Which is why the lines are so close for all the samples.

As illustrated by Figure 4, line (or lines) labelled (B) is different in both shape and position for all the samples. On the one hand, this line could be caused by the recombination inside the Al_{0.3}Ga_{0.7}As barrier. For samples 321 and 343 the position of line (B) is in good agreement with the calculated band gap. Sample 344 has a weak line there as well. On the other hand, for sample 339 line (B) is centred around 1.83 eV, while sample 344 has a line at 1.79 eV. The exact source for these lines is still undefined.

For line (A) the peak energy initially increases with temperature growth, then starts to decrease (Figure 5a), in qualitative agreement with the temperature dependence of GaAs band gap [10] (as could be seen for samples 343 and 344, the line is quickly quenched for the other samples). All lines are eventually quenched with temperature, however the rate is different (Figure 5b). Intensity of line (A) for sample 343 decreases slower than all the other lines.

Acknowledgements
This work was supported by the Russian Foundation for Basic Research (RFBR): grant 16-32-00897.

References
[1] Wu, J et al. 2009 Appl. Phys. Lett. 94 171102
[2] Sakaki, H. 1982 Jpn. J. Appl. Phys. 21 L381L383
[3] Lee, C-D et al. 1998 Appl. Phys. Lett. 73 26152617
[4] Lamas, T E et al. 2005 Thin Solid Films 474 2530
[5] Sibirmovskii Yu D, Vasil’evskii I S, Vinichenko A N et al. 2014 Bull. Lebedev Phys. Inst. 41 243
[6] Sakaki, H, Noda, T, Hirakawa, K, Tanaka, M, Matsusue, T 1987 Appl. Phys. Lett. 51 19341936
[7] Schubert, E F, Knecht, J, Ploog, K 1985 Journal of Physics C 18 L215
[8] McKinnon, W R, Hurd, C M 1987 J. Appl. Phys. 61 22502256
[9] Hurd, C M et al. 1987 J. Appl. Phys. 61 22442249
[10] Levinshtein M, Runyanstek S, Shur M 1996 Handbook Series on Semiconductor Parameters (Singapore: World Scientific)