Tunnelling AFM study of the local density of states in the self assembled In(Ga)As/GaAs(001) quantum dots and rings

D O Filatov, M A Lapshina, M A Isakov, P A Borodin and A A Bukharaev

1 University of Nizhny Novgorod, 23 Gagarin Ave, Nizhny Novgorod 603950 Russia
2 Zavoisky Physical-Technical Institute, Kazan' Scientific Center, Russian Academy of Sciences, 10/17 Sibirskii Trakt, Kazan' 420029 Russia

E-mail: dmitry_filatov@inbox.ru

Abstract. The local density of states (LDOS) in the self assembled In(Ga)As/GaAs(001) quantum dots (QDs) and quantum rings (QRs) was investigated by Tunnelling Atomic Force Microscopy (AFM) at 300K. The peaks in the differential tunnel spectra of the metal coated AFM probe contact to the QDs (QRs) have been observed. These peaks were attributed to the quantum confined states in the QDs (QRs). The patterns of the current images of the QDs (QRs) at the gap voltages corresponding to the maxima of the tunnel spectra were found to reflect the LDOS spatial distribution of the respective quantum confined states. Several electron and hole states were identified.

1. Introduction

Scanning Tunneling Microscopy (STM) is used for the investigation of the morphology and of the atomic structure of the self-assembled semiconductor nanostructures extensively. Recently, STM in Ultra High Vacuum (UHV) has been applied also to the investigation of the spatial distribution of the local density of states (LDOS) in the quantum semiconductor heterostructures. In particular, Cross-Sectional STM has been applied to the investigations of the GaSb/InAs(001) quantum wells (QWs) [1] and of the self-assembled InAs/GaAs(001) quantum dots (QDs) [2]. In [3] the surface InAs/GaAs(001) QDs grown by Molecular Beam Epitaxy (MBE) have been studied by UHV STM in situ. The peaks related to the quantum confined states in the QDs have been observed in the differential conductivity $\sigma_d = dI/dV_g$ spectra of the STM tip contact to the QDs (here $I$ is the tip current and $V_g$ is the gap voltage). The $\sigma_d(x, y)$ images of the QDs (where $x$ and $y$ are the tip coordinates on the sample surface) recorded at the values of $V_g$ corresponding to the peaks in the $\sigma_d(V_g)$ spectra were found to correlate with the probability density patterns $|\chi(x, y)|^2$ where $\chi(x, y)$ are the envelope electron wavefunctions calculated in [4] for the pyramidal InAs/GaAs(001) QDs defined by the (101) facets.

Here we report on the first time application of Tunnelling Atomic Force Microscopy (AFM) [5] to the ex situ investigation of the LDOS in the self-assembled In(Ga)As/GaAs(001) QDs and quantum rings (QRs) grown by Atmospheric Pressure Metal Organic Vapor Phase Epitaxy (AP MOVPE). The samples were covered by the native oxide formed during the sample transfer from the growth chamber to the AFM one through the ambient air that makes the STM studies of these samples hardly possible.
Figure 1. The AFM (a) and current (b) images of the InAs/GaAs QDs. $V_g = -3.7$ V.

2. Experimental

The samples were grown on the n$^+$- and p$^+$-GaAs(001) substrates (for the investigations of the conduction band states in the QDs (QRs) and of the valence band ones, respectively). The GaAs buffer layers $\approx 200$ nm thick were doped by Si (for the n$^+$ substrates) or by Zn (for the p$^+$ ones) heavily (the impurity concentration $\sim 10^{18}$ cm$^{-3}$). The 3 nm thick undoped GaAs spacer layers were grown between the buffers and the InAs QDs. The latter were grown at 530°C, the nominal thickness of InAs was $\approx 5$ monolayers (ML). In order to grow the QRs, the QDs were capped by a 10 nm thick GaAs cladding layer at 600°C. In AP MOVPE the QRs grow just during capping [6] unlike MBE where the post-growth annealing is applied usually [7]. The In molar fraction in the QR material was estimated from the photoluminescence and photoelectric spectra to be 0.35–0.4.

The Tunneling AFM experiments were carried out in Omicron® MultiProbe® UHV system at 300K. The sample was scanned by a conductive Si probe coated by Pt or by W,C in the contact mode. Simultaneously with the acquisition of the AFM images, the current ones $I_t(x, y)$ at the preset values of $V_g$ were acquired. In another mode, the $I_t(V_g)$ curves were acquired in every point of the scans.

3. Results and discussion

The AFM and current images of an InAs/p$^+$-GaAs QD sample are presented in figure 1. An increasing of $I_t$ when the AFM tip contacts the QD surface had been observed that has been attributed to the electron tunnelling between the AFM tip and the conductive buffer through the quantum confined states in the QDs. In figure 2 the $\sigma_d(V_g)$ spectra of the InAs QDs and of the InGaAs QRs are presented. These spectra have been obtained from the measured $I_t(V_g)$ curves of the probe-to-sample contact by numerical differentiation with nonlinear smoothing. The peaks in the $\sigma_d(V_g)$ spectra were related to the quantum confined states in the QDs (QRs) [3]. Comparing the $\sigma_d(V_g)$ spectra of the QDs on the n$^+$-GaAs and on p$^+$-GaAs presented in figures 2 (a) and (b), respectively one can note that the peaks related to the quantum confined states in the n-type QDs are well resolved while in the latter case a nearly exponential curves with the weak oscillations only have been observed. This could be explained noting that according to [4], the energy spacing between the electron levels in the QDs with the base size length $b = 15–20$ nm is $\sim 100$ meV while the one for the hole levels is $10-20$ meV.

In order to associate the positions of the peaks in the $\sigma_d(V_g)$ spectra with the quantum confined level energies one must take into account the voltage drop on the space charge region between the QDs
Figure 3. The AFM (a, e) and current (b—d, f—h) images of the individual InAs QDs on n⁺-GaAs (a—d) and on p⁺-GaAs (e—h). Below the $|\chi(x, y, z)|^2 = 0.65$ surfaces calculated in [4] for the respective electron and hole states $n_1n_2n_3$ in a pyramidal InAs/GaAs(001) QD with $b = 16$ nm are presented.

and the buffer layer [3] and on the surface states at the semiconductor/native oxide interface. Using Hasegawa’s model [8], we have found that $\approx 1/2$ of $V_g$ drops on the surface states.

The AFM and current images of the individual QDs are presented in figure 3. The AFM images of the QDs are rounded and enlarged compared to the actual QD sizes ($b = 14$-$16$ nm) that was attributed to the convolution artifact [9]. The patterns of the $I(x, y)$ images at the $V_g$ corresponding to the maxima of the $\sigma_0(V_g)$ spectra reflect the spatial distribution of the LDOS in the $(x, y)$ plane:

$$\rho_E(x, y) \propto \sum_{n_1n_2n_3=0}^{N_1N_2N_3} |\chi_{n_1n_2n_3}(x, y)|^2.$$ (1)

Here the envelope wavefunctions were considered to be twofold spin-degenerated. The summation in (1) was taken over the states below the Fermi level in the probe coating material $E_F$, i. e. $E_{n_1n_2n_3} < E_F$ for the QDs on n⁺-GaAs, see the inset in figure 3 (a). The above condition defines the upper limits of the summation $N_1$, $N_2$, and $N_3$ in (1). The same holds for the QDs on p⁺-GaAs with altering the energy sign for the holes, see the inset in figure 2 (e).

Following [3], the current images of the QDs were compared to the $|\chi|^2$ patterns of the quantum confined electron and hole states in the InAs/GaAs(001) pyramidal QDs calculated in [4]. The current images were more noisy than the STM ones in [3] that was attributed to the nonuniformity of the native oxide thickness. Nevertheless, several electron and hole states in the QDs were identified, the respective images of the $|\chi(x, y, z)|^2 = 0.65$ surfaces [4] are presented in figure 3.

---

4 Reprinted figures with permission from [4]. Copyright (1999) by the American Physical Society.
The AFM and current images of the QRs are presented in figure 4. The QRs of various diameters $D = 150-400$ nm were observed. The smaller QRs arised from the transformation of the coherent InAs QDs during capping [7] while the larger ones originated from the larger relaxed InGaAs clusters formed by coalescence of the smaller InAs QDs during AP MOVPE growth [6]. Nevertheless, the larger rings could be classified as the QRs as well in spite of their relatively large sizes since the quantum size effect related steps had also been observed in their $\sigma_d(V_g)$ spectra (see figure 2 (c), curve 1).

The observation of the angular patterning in the current images of the QRs was attributed to the asymmetry of the QRs' shape. Otherwise, in the case of a circularly symmetric potential (Curie group of symmetry $C_n$) no such patterning should be observed since in this case the angular part of the envelope wavefunction is expressed in the polar coordinates $(\rho, \phi)$ by the term $\exp(i l \phi)$ where $i$ is the imaginary unity and $l = 0, \pm 1, \ldots$ is the angular quantum number, and $\exp(i l \phi)^2 = 1$ for any $\phi$. In addition, one should take into account the effect of the piezoelectric field in the strained InGaAs [4], which also reduces the potential symmetry downto $C_2v$ even in a perfectly round QRs.

4. Conclusion

The results of the presented study demonstrate applicability of Tunnelling AFM to the ex situ investigations of the LDOS of the quantum confined states in the In(Ga)As/GaAs nanostructures covered by the native oxide. The observed patterns of the current images agree with the results of the QD eigenfunction calculations present in the literature. The current images of the QRs were related to the asymmetry of the confining potential.

Acknowledgments

The present work was supported in part by Russian Federal Agency for Education (NK-346P-25). The authors are grateful to B N Zvonkov (Research Institute for Physics and Technology, N I Lobachevskii University of Nizhny Novgorod) for growing the samples for investigations.

References

[1] Suzuki K, Kanisawa K, Janer C, Perraud S, Takashina K, Fujisawa T and Hirayama Y 2007 Phys. Rev. Lett. 98 136802
[2] Grandidier B, Niquet Y M, Legrand B, Nys J P, Priester C, Stievenard D, Gerard J M and Thierry-Mieg V 2000 Phys. Rev. Lett. 85 1068
[3] Maltezopoulos T, Bolz A, Meyer C, Heyn C, Hansen W, Morgenstern M and Wiesendanger R 2003 Phys. Rev. Lett. 91 196804
[4] Stier O, Grundmann M and Bimberg D 1999 Phys. Rev. B 59 5688
[5] Olbrich A, Ebersberger B and Boit C 1998 Appl. Phys. Lett. 73 3114
[6] Baidus' N V, Zvonkov B N, Filatov D O, Guschina Yu Yu, Karpovich I A and Zdorovesischev A V 2000 J. Surf. Inv. 7(2004) 71
[7] Lorke A and Luyken R J 1998 Phys. B 256 424
[8] Hasegawa H and Sawada T 1983 Thin Solid Films 103 119
[9] Bukharae A A, Berdunov N V, Ovchinnikov D V and Salikhov K M 1998 Scanning Microsc. 12 225