The diagram of *p-n* junction formed on the *n*-GaAs-surface by 1.5 keV Ar^+ ion beam

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Abstract. The core-level and valence band electronic structure of the *n*-GaAs (100) has been studied by synchrotron-based high-resolution photoelectron spectroscopy after irradiation by an Ar^+ ion beam with energy E_i = 1500 eV and fluence $Q = 1*10^{15}$ ions/cm^2. Conversion of the conductivity type of the surface layer and formation of a *p*-*n* structure has been observed. The *p*- surface layer thickness (d ~ 5.0 nm) and band structure were experimentally determined from the Ga3d photoelectron spectrum by separation and analysis of the low intense *n*- type bulk contribution from deeper layers. A band diagram of the *p*-*n* junction formed on the *n*-GaAs-surface by Ar^+ ion bombardment was reconstructed. The *p*-*n* junction proved to be unexpectedly narrow compared to the extended tail of the implanted ion depth distribution.

Key words: GaAs, *p*-*n* junction, band structure, ion irradiation, Ar^+ ion beam

1. INTRODUCTION

GaAs and GaAs-based semiconductors are ones of the most important materials for modern high- frequency electronics [1]. Therefore, development of new approaches to fabrication of GaAs-based devices seems to be a topical problem. Recently, the process of the *p*-nanolayer creation on the GaAs surface under Ar^+ ion bombardment has been revealed [2]. Argon atoms cannot directly change electrical properties of the implanted layer due to their chemical neutrality. Moreover, argon mainly escape the irradiated layer due to diffusion after thermalization. The *p*-layer creation effect was shown to be related to formation of the Ga-antisite *p*-type centers due to mechanical action of ions. In addition, the effect of a *p*-*n* structure formation on the *n*-GaAs surface by low energy Ar^+ ions has been observed. *J–V* characteristics of the created *p*-*n* structure revealed the diode effect [3]. The attractiveness of the studied approach for possible applications is that the *p*-*n* junction can be formed in a high vacuum locally with the lateral resolution determined by the ion beam diameter without using the wet lithography. Despite obtaining some information about the ion-beam made *p*-*n* structure, such important characteristics as *p*-layer thickness and band diagram of the *p*-*n* junction have been estimated only qualitatively. By using synchrotron based *X*-ray photoelectron spectroscopy, we directly determined in this paper the thickness of a *p*- layer and binding energies of electrons at the valence band edge, which allowed deducing a band diagram of the *p*-*n* junction formed on the *n*-GaAs-surface under Ar^+ low energy ion irradiation.

2. METHODS

The experiment was carried out in ultrahigh vacuum at the Russian–German synchrotron radiation beamline of the BESSY-II electron storage ring of Helmholtz-Zentrum Berlin [4] by using the photoelectron spectrometer with hemispherical analyzer CLAM-4 (VG). The photoelectron (photoemission) spectra were measured at the normal direction from the sample irradiated by a monochromatic *X*-ray photon beam at the angle $\theta = 55^o$. The photon energy scale of the plane-grating monochromator (RG-PGM) was regularly calibrated using the Au $4f_{7/2}$ line of gold in order to maintain the accuracy of the binding energy determination better than ± 0.05 eV. The total energy resolution was ΔE < 300 meV. The spectra were measured at photon energies from the range $h\nu$ = 150 - 350 eV providing different information depths. A commercial GaAs (100) *n*-type (n ~ 1.25 – $2.5*10^{18}$ cm^{-3}) wafer was irradiated by Ar^+ ions with energy E_i = 1500 eV in the preparation chamber of the spectrometer. The dose density (fluence) $Q = 1*10^{15}$ ions/cm^2 was sufficient to remove completely the layer of native oxide and a part of the bulk layer. The survey spectrum measured at the photon energy ($h\nu$ = 650 eV) sufficient for observation of the O1s line exhibited virtual absence of oxygen and carbon as well as of possible impurities, which evidenced removal of the native oxide layer and purity of the ion beam.

3. RESULTS AND DISCUSSION

The *p*-type conductivity of the irradiated layer is confirmed by the valence band (VB) photoelectron spectrum represented in Fig. 1. The spectrum characterizes the density of occupied VB states just of the surface layer whose thickness is determined by the photoelectron mean free path λ = 1 nm [5]. The electron binding energy scale is counted relative to the Fermi level. Extrapolation of the spectrum top enables determination of the valence band edge position which, as the figure shows, is only 0.35 eV below the Fermi level. This value proved to be a bit larger compared to that (0.25 eV) observed for higher Ar^+ ion energy E_i = 2500 eV and an order of magnitude higher dose [2]. Closeness of the valence band top to the Fermi level evidences for conversion of the conductivity type of the near-surface layer under ion bombardment from *n*- to *p*-type. The conductivity type transformation was accounted for by the preferable sputtering of arsenic atoms and enrichment of the irradiated layer

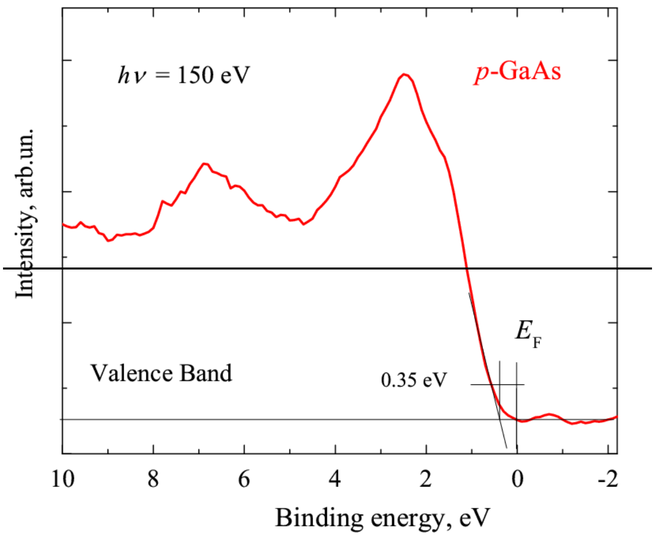

Fig. 1. Valence band (VB) photoelectron spectrum of the *p*-GaAs nanolayer formed on the *n*-GaAs(100) surface by Ar^+ ion irradiation.

with gallium, followed by the creation of the Ga-antisite *p*-type centers [2]. Since the initial sample is *n*-type, a *p*–*n* structure is formed.

The VB spectrum shown in Fig. 1 was measured at photon energy $h\nu = 150$ eV. The corresponding photoelectron kinetic energy provides the small information depth of the order of photoelectron mean free path $\lambda = 1$ nm [5] which is insufficient to probe the thickness of the *p*-layer. Preliminary information about the thickness $\langle x \rangle$ of the irradiated layer was acquired from calculations with the commonly known TRIM 2006 code [6]. The thickness was estimated as the width at the half maximum of the depth profile which is approximately equal to the value $\langle x \rangle = 2R_p = 5.4$ nm, where R_p is the projected range calculated by the TRIM code with more ease.

The *p*- layer thickness was obtained also experimentally from Ga3d photoelectron spectrum by separation and analysis of the *n*-type bulk contribution. This contribution should be found at the high energy side of the spectrum which corresponds to the Fermi level shift from CB to VB. Indeed, the binding energy shift in band structure terms is: $\Delta E_B = \varphi_o = \mu_n - \mu_n \sim 1$ eV, where μ_n and μ_n are the Fermi level energies in *n* and *p* type semiconductors, and φ_o is the contact potential difference Figure 2 shows the Ga3d photoemission spectra in the electron binding energy scale at two photon energies *hv* = 150 (dotted line) and 350 eV (solid line) which characterize thin and thicker material layers. The peaks for both photon energies coincided in energy (E_B = 19.35 eV) and proved to be very close to our former data for GaAs irradiated by Ar^+ ions [2] and to the data known from literature [7]. This energy is a characteristic of the irradiated near-surface *p*-layer. As was shown above, the contribution of the unirradiated *n*-type bulk should be expected at the ~ 1 eV higher binding energy (E_B ~ 20.35 eV) where the difference between the compared spectra is observed (Fig. 2). This difference reveals a small but statistically reliable contribution at binding energy E_B = 20.15 eV which was identified as belonging to the top of the *n*-GaAs bulk underneath the modified *p*-GaAs layer. The bulk signal occurred to be rather weak due to attenuation in the upper layer. Figure 2 also shows the presence of interstitial/metallic Ga (Ga-*int*) in the *p*-layer at binding

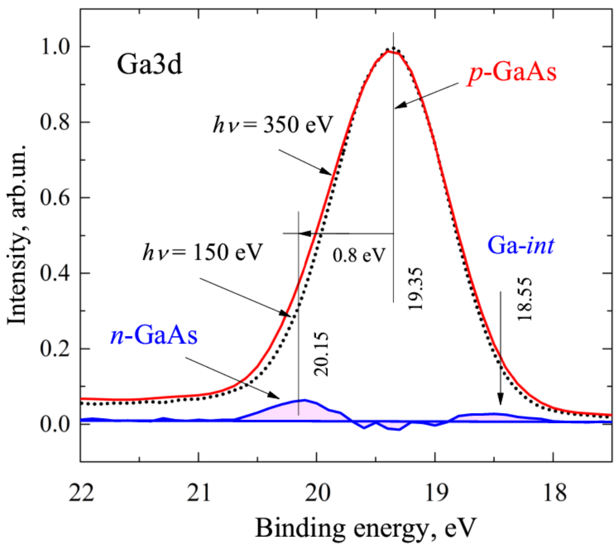

Fig. 2. Ga3d photoelectron spectra of the *n*-GaAs sample irradiated by 1500-eV Ar^+ ion beam and their difference (shaded area). The spectra were measured with photon energies *hv* = 150 eV (dotted line) and *hv* = 350 eV (solid line).

energy E_B = 18.55 eV discussed elsewhere [2,3]. A kink at binding energy E_B = 20.2 eV was revealed also in the doubly differentiated spectrum (not shown here), thus confirming the presence of the bulk *n*-GaAs contribution.

The binding energy (E_B = 20.2 eV) of the Ga3d contribution revealed for *n*-GaAs and corresponding line shift (~0.8 eV) proved to be less than those (E_B = 20.35 eV; ~ 1.eV) estimated above. The obvious reason is connected with the probing depth ($l \sim 3\lambda$ = 5.4 nm) being sufficient to observe only the upper part of the *p*-GaAs/*n*-GaAs interface. The band diagram with realistic extended interface is shown in Fig. 3 together with implanted ion depth profile in the scale of the distance from the surface. The effective thickness of the *p*-GaAs layer was estimated both by TRIM code (see above) and experimentally by comparison of intensities (I_p and I_n) of the *p*- and *n*- contributions to the Ga3d line intensity:
$d = \lambda\ ln(I_p/I_n +1)$. The experimental estimation gives the value d = 5.0 nm which proved to be very close to the calculated thickness $\langle x \rangle \sim 2R_p$ = 5.4 nm of the irradiated layer. A replicate experiment gave a close value. The position of the valence band edge (- 0.8 eV) corresponding to the obtained thickness (5.0 nm) is shown as an experimental point (circle) in Fig. 3b. Two experimental points (triangles) defining the VB edge in the *p*-layer were obtained from VB and Ga3d photoelectron spectra measured at photon energies $h\nu$ = 150 and 350 eV. Position of the VB edge in the deep bulk is defined by the known band gap. The extension of the VB edge tail in the deep balk is determined by the area of space charge which is equal to ΔL = 40 nm at the condition when the acceptor concentration essentially exceeds that of donors (n ~ $1.25 \cdot 10^{18}$ cm^{-3}). These conditions make the shape of the reconstructed *p-n* band structure rather definite. The unexpected result following from the reconstructed diagram is that the *p-n* junction is pretty narrow when compared to the extended tail of the implanted ion depth distribution and full space charge length.

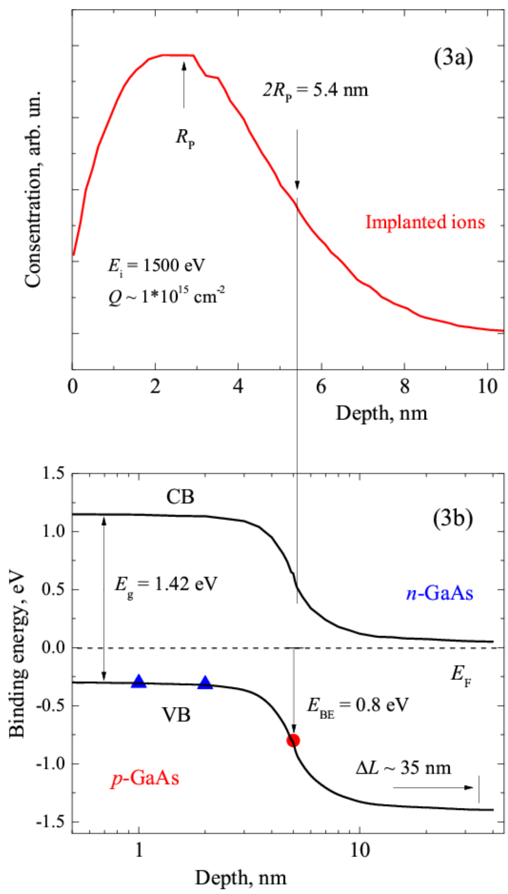

Fig. 3. (a) Depth distribution of the Ar^+ ions implanted into the *n*-GaAs (100) sample. (b) Band diagram of the *p*-GaAs nanolayer formed on the *n*-GaAs (100) surface by Ar^+ ion irradiation. Triangles and circle are the experimental points.

4. CONCLUSIONS

Imparting a *p*-type conductivity to GaAs layer and formation of a *p*-*n* structure on the *n*-GaAs surface has been observed under irradiation by Ar^+ ions with low energy (E_i = 1500 eV) and relatively low fluence (Q = $1*10^{15}$ ions/cm^2). The conductivity type conversion occurs due to purely mechanical action of chemically neutral argon diffusing away after implantation. The effect manifests itself in shifting the valence band edge to the Fermi-level and fixing it 0.35 eV below Fermi-level. This gap proved to be a bit larger compared to that (0.25 eV) previously observed for higher Ar^+ ion energy E_i = 2500 eV and greater fluence (Q = $1*10^{16}$ ions/cm^2). The *p*-layer thickness was estimated by TRIM as the double projected range of implanted ions ($\langle x \rangle = 2R_p = 5.4$ nm) and was obtained experimentally ($d = 5.0$ nm) from the Ga3d photoelectron spectrum by separation and analysis of the *n*- type bulk contribution from deeper layers. The binding energy of this contribution was found and, finally, a band diagram of the *p*-*n* junction formed on the *n*-GaAs-surface under Ar^+ ions was reconstructed. The *p*-*n* junction proved to be unexpectedly narrow in comparison with the extended tail of the implanted ion depth distribution and full space charge length. This fact seems to make attractive the ion beam approach to direct formation of the diode structures on GaAs.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest related to this work.

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