# DIODE EFFECT OF THE *p-n* STRUCTURE FORMED ON THE *n*-GaAs SURFACE BY LOW-ENERGY $Ar^+$ IONS

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## Introduction

Low-energy $Ar^+$ ions are widely used to prepare atomically clean material surfaces necessary for diagnosing them by surface-sensitive techniques in ultrahigh vacuum [1]. Among those techniques, the most common is x-ray photoelectron spectroscopy (XPS) conventionally used for chemical analysis [1]. It is typically assumed that ion bombardment does not modify the near-surface layer properties with respect to those of the bulk material and, hence, the acquired information applies to the material as a total. This assumption is based on the fact that ion irradiation does not change the short-range order and, hence, the atom chemical states. However, the recent study of valence-band photoelectron spectra of the *n*-GaAs atomically clean surface has revealed that an irradiated layer of the nanometer thickness changes its conductivity type and becomes a *p*-layer [2]. Since the initial material is an *n*-type semiconductor, we may conclude that the $Ar^+$ ion bombardment causes the formation of a *p-n* structure and, possibly, a *p-n* junction.

In this study we have measured *J-V* Characteristics (JVC) of the formed structure and proved the presence of the diode effect.

## Results and Discussion

Fig. 1(a) presents a TRIM profile of $Ar^+$ ions implanted into GaAs with energy $E_i$ = 2500 eV. Using this profile, we assessed the thickness of the ion-modified layer. The thickness was assumed to be the $Ar^+$ distribution FWHM, hence, $d \sim 2R_P$ = 7.8 nm, where $R_P$ is the projected range. The thickness estimate was close to the layer thickness obtained by measuring the *p-n* structure profile by photoelectron spectroscopy with varying the probing depth [4].

Fig. 1(b) demonstrates the band diagram of the *p-n* structure formed on the *n*-GaAs surface by the $Ar^+$ ions implantation. The dotted line represents the Fermi level. In the near-surface region where the implanted ion concentration is high, the valence band top is adjacent to the Fermi level, while in the deep weakly modified layer the conductivity band bottom is close to the Fermi level.

Fig. 2 presents dark JVCs of one of the experimental irradiated samples (*p-n* GaAs) and a reference unirradiated sample (GaAs-ref.) measured in the forward (Forward) and reverse (Reverse) directions. One can see that the difference between the forward and reverse currents reaches 2.5 orders of magnitude. This means that the *p-n* structure JVCs demonstrate the existence of the diode effect, contrary to JVCs of the unirradiated reference sample (GaAs-ref.) whose forward and reverse currents are equal.

Fig. 3 presets the forward dark JVC of one of the experimental samples (Experiment) in comparison with JVC calculated according to the two-exponential model (Silvaco-modeled). This JVC curve represents the dependence in a considerably wider range of voltage (up to 0.7 V), which is probably caused by a better adhesion of the metal layer with the front surface of the sample. The metal contacts were applied by the non-conventional technique of cold contact application. To prove that the observed diode effect is not caused by formation of the Schottky barrier on the front side of the irradiated sample, JVCs for the *p–n* structure shown in Fig. 1 with the supposedly ohmic contacts were calculated using the "*Silvaco*" code [3]. The simulated JVC (Silvaco-modeled) almost ideally fits the experimental curve.

## Acknowledgements

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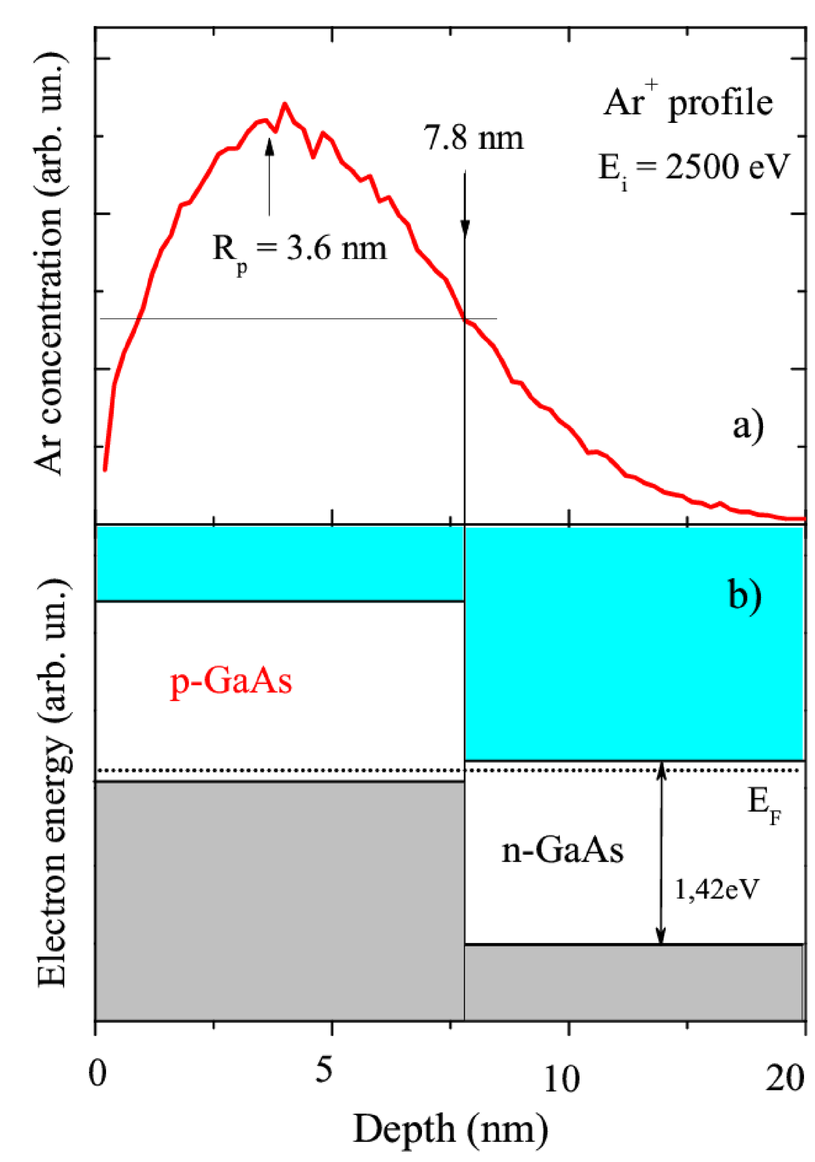


**Fig. 1.** (a) A TRIM profile of $Ar^+$ ions implanted into GaAs with energy $E_i$ = 2500 eV. (b) A band diagram of the *p-n* structure formed on the *n*-GaAs surface by the $Ar^+$ ions implantation.

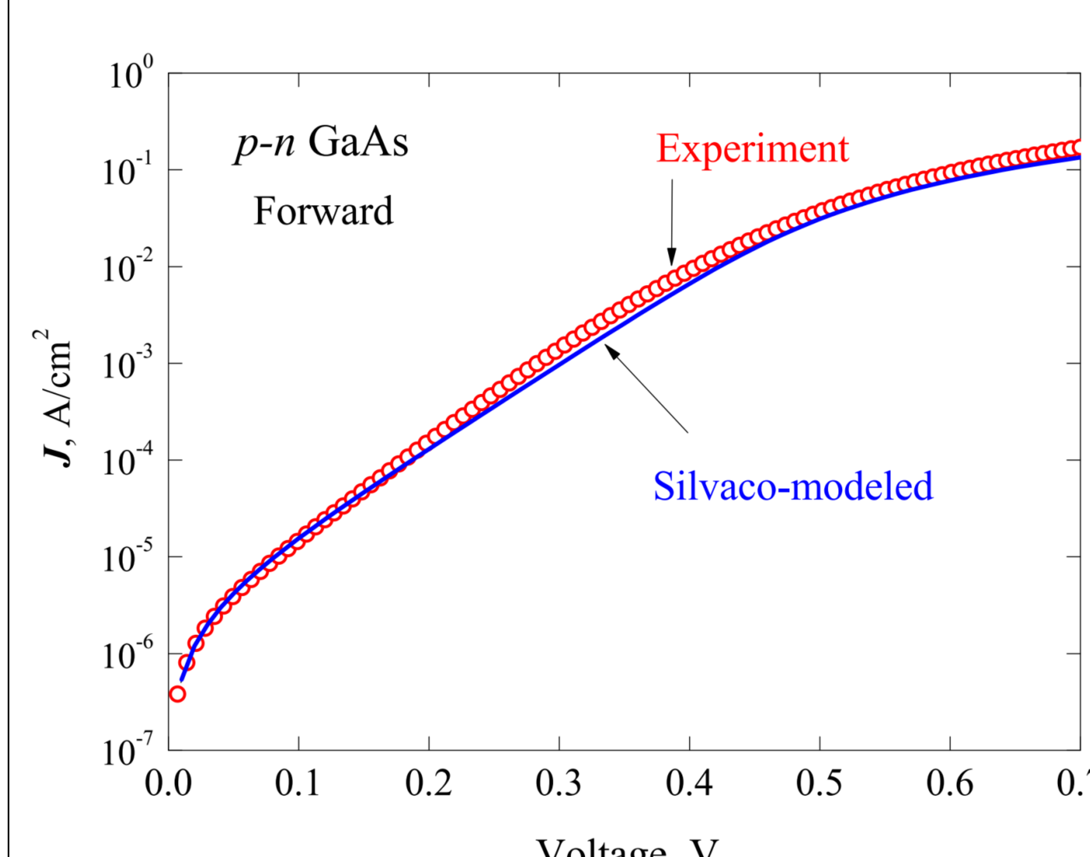


**Fig. 3.** The forward dark JVC of one of the experimental samples (Experiment) in comparison with JVC calculated according to the two-exponential model (Silvaco-modeled).

## References

[1] D. Briggs, M.P. Seah, Eds., Practical Surface Analysis by Auger and X-Ray Photoelectron Spectroscopy, John Wiley & Sons, New York, 1983.
[2] V.M. Mikoushkin, V.V. Bryzgalov, S.Yu. Nikonov, A.P. Solonitsyna, D.E. Marchenko, EPL **122**, 27002 (2018).
[3] Silvaco Atlas User's Manual Device Simulation Software, URL :http://ridl.cfd.rit.edu/products/Manuals/Silvaco/atlas_users.pdf
[4] V.M. Mikoushkin, E.A. Makarevskaya, A.P. Solonitsyna, M.M. Brzhezinskaya, *Semiconductors* 54, 1702 (2020).

## Experimental details

As the subject of research, an *n*-GaAs (100) (n ~ $10^{18}$ $cm^{-3}$) wafer was used. The sample was irradiated with $Ar^+$ ions with energy $E_i$ = 2500 eV in ultrahigh vacuum (~ 5 × $10^{-10}$ Torr) in the operating chamber of electron spectrometer Leybold-AG. Fluence $Q$ ~ 1 × $10^{15}$ $cm^{-2}$ was sufficient to remove the natural oxide layer and a formation of an ion-modified layer. Dark JVCs were measured under atmospheric conditions at room temperature. For this purpose, ohmic contacts were applied on the front and back sides of the sample. Prior to applying the contacts, the samples were chemically etched and rinsed. The metal contacts 0.2 μm in total thickness were applied by thermal evaporation ($T_{sam}$ < 100°C) of Ni, Au and Ag in high vacuum (~ 5 × $10^{-7}$ Torr). The obtained experimental dependences were compared with those calculated with code "*Silvaco*" [3].

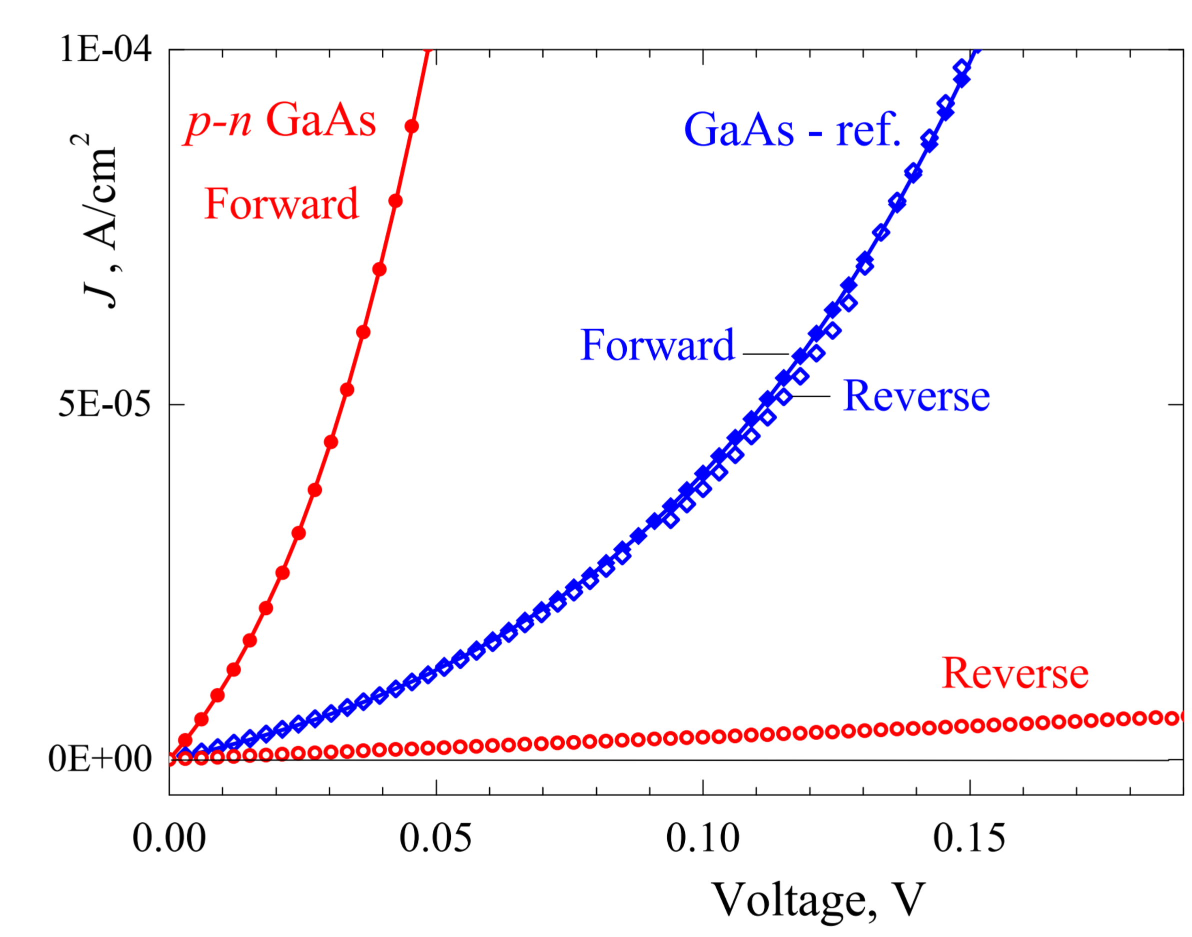


**Fig. 2.** Dark JVCs of one of the irradiated experimental samples (*p-n* GaAs) and an unirradiated reference sample (GaAs-ref.) measured in the forward (Forward) and reverse (Reverse) directions.

## Conclusions

Investigation of electrophysical properties of the *n*-GaAs surface modified by purely mechanical impact from chemically neutral argon ions has revealed the presence of the diode effect. This means that bombardment of the *n*-GaAs surface with low-energy $Ar^+$ ions results in formation of the *p–n* structure with a *p–n* junction.

For the JVC measurements, a technique of cold application of ohmic contacts on an extremely thin ion-modified layer was developed.

The model JVC has confirmed formation of a semiconductor *p–n* junction with preferentially ohmic contacts.