Transport charge of gallium arsenide films synthesized on polycrystalline silicon by ion ablation

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Abstract. Electrophysical and photoelectric properties of thin GaAs films deposited on polysilicon by pulse ion ablation using high-power ion beams have been investigated. The predominant charge carriers transfer mechanism in films and the type of dark and photoconductivity have been established. A vacuum annealing effect (10^{-2} Pa, 300–1000 K) on energetic and kinetic characteristics of dark and photoconductivity, the transfer mechanism and the type of charge carriers have been determined. The most probable causes of changes in the film electric and photoelectric characteristics have been discussed.

1. Introduction
Gallium-arsenide and silicon are prospective materials for electronics. Their production has been developed; they obtain a perfect combination of electric and photoelectric parameters, radiation hardness and thermal stability of properties [1–4]. Uniting these materials on one substrate is an upcoming trend in optimization of the optoelectronic device production technology [1–3, 5]. While growing GaAs on Si, there are some problems that are connected with the growth of a polar semiconductor on a non-polar substrate, with the difference in lattice parameters (up to 4 %) and the thermal expansion coefficient. Antiphase domains are formed, stress and high dislocation density near the boundary arise [1, 2]. Defects worsen the parameters of devices based on GaAs/Si [1–3]. The problems of the GaAs epitaxial deposition on Si are partially overcome by applying cycle annealing [3] and by creating thin joining transition layers [1].

Electric characteristics and charge carriers transfer mechanisms in crystalline epitaxial grown c–GaAs vary over a wide range [3–6]. The unique properties of amorphocrystalline a–GaAs films deposited from RF–plasma by impulse methods [6, 7], thermal deposition, co–evaporation of the elements [8] and laser deposition [9] enable to use them in the production of layers that match lattice parameters during the deposition of GaAs/Si and heterostructures on their basis. The characteristics of such films differ from c–GaAs due to their complex structure and strong defect disordering. Film deposition from plasma produced by a powerful ion beam (PIB) enables to implement high-speed deposition and to form films on significant areas and on various substrates [10–13]. The peculiarities of electromigration in the films synthesized by the pulse ion ablation (PIA) have been insufficiently studied.

Electric and photoelectric characteristics, the transfer mechanism, the type of charge carriers in thin GaAs films synthesized on polysilicon by PIA have been investigated in this article. The energy spectrum of defect levels, featuring material properties, has been specified.
2. Experimental

The films have been obtained by means of the TEMP accelerator at sequential deposition on polysilicon and polycor. The method of film deposition has been described in [10]. The annealing was carried out in vacuum (pressure $P \leq 10^{-2}$ Pa, $T_{\text{ann}} = 300–1000$ K). Surface $\sigma_s$ and bulk $\sigma_v$ dark and photoconductivity $\Delta \sigma_{ph} = \sigma_{ph} - \sigma$ ($\sigma_{ph}$–conductivity under lighting), photosensitivity $K(h\nu) = \Delta \sigma_{ph}/\sigma$ were measured at constant electrode voltage $U = 0.01–300$ V, at temperature $T = 300–700$ K and at photon energy $h\nu = 1.5–4.0$ eV [12, 13]. The electrodes were deposited onto the film surface by silver thermal spraying. The temperature dependences $\sigma$, $\Delta \sigma_{ph}(T)$ were approximated by the equation for activation mechanism

$$\sigma_a(T) = \sigma_0 \times e^{(-\epsilon_\sigma / k T)}$$

(1)

where $\sigma_0$ is a pre-exponential factor, $\epsilon_\sigma$–an activation energy, $k$– Boltzmann constant and by the equation for transfer hopping mechanism on localized states (LS) near the Fermi level $E_F$ within the Mott model

$$\sigma'_a(T) = \sigma'_0 \times e^{(-\epsilon_{\sigma}/T)^{1/2}}$$

(2)

where $\sigma'_0$ is a pre-exponential factor, $T_0$ is an activation energy [6, 12]. State density $N(E_F)$ near $E_F$ was calculated according to $T_0$ in compliance with [6, 12]. The sign of dominant charge carriers was determined according to the method [12].

3. Result and discussion

Temperature dependences $\sigma$, $\Delta \sigma_{ph}(T)$ of films is due to LS with $\epsilon_\sigma = 0.05–0.16$ eV within the interval $T = 300–500$ K at the charge carriers exchange between LS and the allowed bands. N–type of $\sigma$ and $\Delta \sigma_{ph}$ predominate in GaAs/Si, whereas, the concentration of LS donors is higher in comparison with the one of acceptors. The effect of donors increases in the films deposited on the periphery [11, 12]. In the centre of deposition, defect contribution increases with their possessing shallow acceptor LS with energy $\epsilon = E_v + (0.05–0.16)$ eV, where $E_v$ is a valence band (VB) top. Values $\sigma$, $\Delta \sigma_{ph}$, $K$ for $\sigma_v$ are higher as compared to $\sigma_s$ due to the influence of shallow acceptors (figure1). The comparison of film characteristics on silicon and polycor under the same deposition and measurement conditions showed the advantage of GaAs/Si in values $\sigma$, $\Delta \sigma_{ph}$ and their field excitation and heating stability (figure 1). This is due to the heterogeneous distribution of trapping centers and recombination near GaAs/Al$_2$O$_3$ boundary [14, 15]. In the case of Al$_2$O$_3$, the effect on the charge transfer barrier between GaAs VB and the conduction band (CB) bottom is more significant (a barrier $\Phi > 3.2$ eV) [15].

The relations between values $\epsilon_\sigma$ and $\sigma_0$ are conditioned by the high content of defects in films as compared to c-GaAs and by the influence of a hopping component $\sigma_h$ involving LS defects similar to the approach [5–8, 12]. The approximation of curves $\sigma$, $\Delta \sigma_{ph}(T)$ indicates the predominance $\sigma_h$ over $\sigma_s$, within the interval $T = 300–500$ K in PIA films. The most probable hopping length is $R = 4.5–7.6$ nm with the calculated values of $N(E_F) = (0.74–3.2) \times 10^{18}$ eV$^{-1}$ cm$^{-3}$ (figure 2, curve 1). Values $N(E_F)$ of deposited GaAs/Si films are closer to the density of LS films obtained by co-evaporation of elements than to their values in films on polycor (figure 2) [8, 12]. The hopping conductivity is the main migration mechanism in LT–GaAs [4, 5]. The comparison with LT–GaAs enables to suggest that $E_F$ is fastened near the middle of the band gap (BG) at $\epsilon = E_v + (0.6–0.8)$ eV in GaAs films deposited by PIA [4–7]. This is due to high concentration of $N > 10^{18}$ cm$^{-3}$ of defects like EL$_2$–centers (As$_{Ga}$Ga$_{Si}$, pairs As$_{Ga}$V$_{Ga}$, As$_{Ga}$As$_2$) creating LS deep within BG [4, 5, 12, 13]. The hole exchange between the shallow acceptor LS and VB dominates at $T = 300–500$ K and the electron exchange between donor LS and CB – under light excitation, as $K(U, T)$ show. Values $\epsilon_\sigma$ for $\Delta \sigma_{ph}(T)$ are lower than $\sigma(T)$ possesses on ~0.05 eV, whereas hopping length decreases from $R = 4.5–7.6$ to $3.6–5.5$ nm. LS occupation by charge carriers decreases, while the density $N(E_F)$ increases 1.8–4 times, which is typical of most materials [6, 12].
Vacuum annealing modifies the electronic state of film materials in consequence of its partial crystallization, the change in the defect charge state and the formation of defect complexes [5, 7, 8, 11–13, 15]. LS density near the film surface and on the boundary with substrate changes, arsenic clusters form [4, 8, 12]. According to characteristic change, two annealing stages $T_{\text{ann}}=300–600, 600–1000$ K (figures 1–3) are distinguished. Correlation dependences $N(E_F)(\sigma_0)$ and $N(E_F)(\epsilon_\sigma)$ divided into two branches for bulk and surface conductivity are implemented between parameters $\sigma_h$ and $\sigma_a$ (figures 4, curves 1 and 2). The correlation between contributions to the electric conduction of the components $\sigma_a$ and $\sigma_h$ changes (figures 1–4).

After $T_{\text{ann}}=300–600$ K the change in GaAs/Si film characteristics differs from the films on polycor (figures 1–3). The decrease in $\sigma$ of GaAs/Al$_2$O$_3$ films correlates with the increase in LS density (figures 1, 2) [12, 15]. At maxima $\sigma$, $\Delta\sigma_{\text{ph}}$, $K$ at $T_{\text{ann}}=350–450$, $K$ and $\epsilon_\sigma$ approaches maximum $\epsilon_\sigma=0.05–0.08$ eV, while LS maximum density is $N(E_F)=(3–4)\times10^{18}$ eV$^{-1}$cm$^{-3}$, which indicates the increase in contribution of $\sigma_h$ (figures 1–3). The relaxation of nonequilibrium charge carriers and their recombination between shallow LS and deep levels with $\epsilon>1.4$ eV defects take place, which is confirmed by spectra $K(h\nu, T_{\text{ann}})$ [11–13]. At $T_{\text{ann}}=450–600$ K the correlation between the decrease in $\sigma$, $\Delta\sigma_{\text{ph}}$, the increase in $K$ and $\epsilon_\sigma$, the decrease in $N(E_F)=4\times10^{18}$ to $6\times10^{16}$ eV$^{-1}$cm$^{-3}$ is observed, which indicates the increase in contribution to the activation mechanism electromigration (figures 1–3). As $K(U)$ show, the effect of light-generated holes in VB on $\Delta\sigma_{\text{ph}}(T, U)$ increases. The properties are affected by the defect annealing and recharging, as well as the dissociation of unstable complexes [11, 13]. The dependences $N(E_F)(\sigma_0, \epsilon_\sigma)$ indicate less disordering of GaAs/Si films by defects in comparison with GaAs/Al$_2$O$_3$ and a–GaAs films (figure 4) [6–8, 12].

After $T_{\text{ann}}=600–1000$ K the change in parameters $\sigma$ and $\Delta\sigma_{\text{ph}}$ indicates the increase in the influence on the properties of charge carrier processes in the substrate Si (figures 1–3). State density stabilizes at $N(E_F)=(5–10)\times10^{16}$ eV$^{-1}$cm$^{-3}$, whereas the hopping length increases from $R=3.6–5.5$ to $10–15$ nm unlike the films on polycor, where $N(E_F)$ and contribution of $\sigma_h$ increase and $R$ decreases (figure 2).
The annealing effect on activation energy $\varepsilon_{\sigma}$ in GaAs films synthesized by PIA on silicon (curve 1) and on polycor (curves 2, 3) using the low-resistance target [12]. Data for a-GaAs films deposited from RF-discharge plasma (curve 4) [7] and co-evaporation (curve 5) [8] are presented.

The recession of $\varepsilon_{\sigma}$ in GaAs/Al$_2$O$_3$ films takes place at 130–230 K higher than in GaAs/Si films (figure 3). Ion implantation in polycor also has its influence [11, 12]. The relation typical of the strong defective GaAs is implemented between LS parameters, which allows to conclude that structural disorder in the films on polycor is higher than in the films on silicon, while its efficiency is determined by the deposition conditions (figures 2–4) [6–9, 12]. Fractional crystallization of film material, growth defect annihilation and recharge, clustering and enlargement of nanoparticles are probable reasons for changes in parameters $\sigma$, $\Delta\sigma_{ph}$ [11–13].

4. Conclusion
Electric conductivity and photoconductivity of GaAs films deposited by PIA using PIB on the silicon substrate has a mixed type. It is implemented by means of the activation and hopping mechanism involving conditions caused by defects localized in BG near the Fermi level. Two annealing stages at $T_{ann}$ K are distinguished: 300–600 and 600–1000; they are characterized by different relations between parameters LS and transfer mechanisms. After 300–600 K the changes in conductivity characteristics are caused by charge carrier redistribution between the shallow and deep levels of donor and acceptor defects. At 600–1000 K the parameters of surface and bulk dark and photoconductivity, transfer mechanisms are caused by recharge, the annihilation of defects and their clustering.

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