

# Surface Structure and Electrical Properties of Ge Films on Semi-insulating GaAs Substrates

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*Abstract* – Structural, electrical and optical properties of Ge films on semi-insulating GaAs substrates have been investigated. X-ray and electron diffraction, atomic force microscopy (AFM), multiangle ellipsometric and galvanomagnetic (Hall effect, resistance and magneto-resistance) measurements have been used for these investigations.

## I. INTRODUCTION

Ge/GaAs heterostructure can be used for fabrication of a number of types of electronic devices, such as photodetectors, diodes and sensors of temperature, magnetic field and strain [1]-[4].

It is well known [1], [2] that optical and electrical properties of Ge films and heterojunctions are strongly depended on the technological conditions of heretostructure formation. So study of the details of these dependencies is of interest for both semiconductor materials science and instrument device fabrication.

This paper deals with investigation of Ge films on semi-insulating GaAs substrates prepared by thermal evaporation of Ge in vacuum. We used the following methods:- (i) ellipsometry; (ii) x-ray and electron diffractometry; (iii) atomic force microscopy (AFM); and (iv) galvanomagnetic effects.

## II. PREPARATION AND PARAMETERS OF THE FILMS

Ge films were obtained using thermal evaporation in a vacuum onto semi-insulated GaAs (100) substrates. During Ge deposition process the substrate temperature was varied from 120 to 450 °C. The film thicknesses were varied from 0.8 up to 1.5 μm. The film parameters at 300 K are presented in Table I.

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TABLE I  
PARAMETERS OF Ge FILMS

No.	Film structure	Resis- tivity Ω×cm	Hall mobility cm <sup>2</sup> /V×s	Concentra- tion cm <sup>-3</sup>
449	single- crystalline	0.076	560	1.56× 10 <sup>17</sup>
632	mosaic single- crystalline	0.035	222	8.2× 10 <sup>17</sup>
630	polycrystalline	0.110	49	1.13× 10 <sup>18</sup>
2	amorphous	-	-	-

## III. RESULTS AND DISCUSSIONS

### A. X-ray and Electron Diffractometry

The crystalline structure of Ge films was studied using x-ray and electron diffractometry. The films were of different degrees of structural perfection. Their main feature was block structure with disorientation of individual single-crystalline blocks up to several degrees. The sample #449 had the most perfect structure with the largest blocks.

The electron diffraction pattern of sample #630, along with intense spots from the host crystal, demonstrated spots of lower intensity from twins and diffraction rings from randomly-oriented crystallites of the polycrystalline phase.

The sample #2 had amorphous structure. Its annealing in the diffractometer column at 300±20 °C resulted in transformation of amorphous film into polycrystalline one. Its grains were mostly as large as several tens of nm. Point reflections from larger crystallites were present too.

### B. Atomic Force Microscopy

AFM supplies with information on solid-state surface relief. Surface relief for samples #632 and #630 are presented in Fig. 1. On the surface of sample #632, along with random surface height spread of ±1 nm, there is a system of pits. Their size is from 100 to 300 nm, and they are 10–12 nm deep. The pits are grouped in chains and form a square net-like structure with individual cells of about

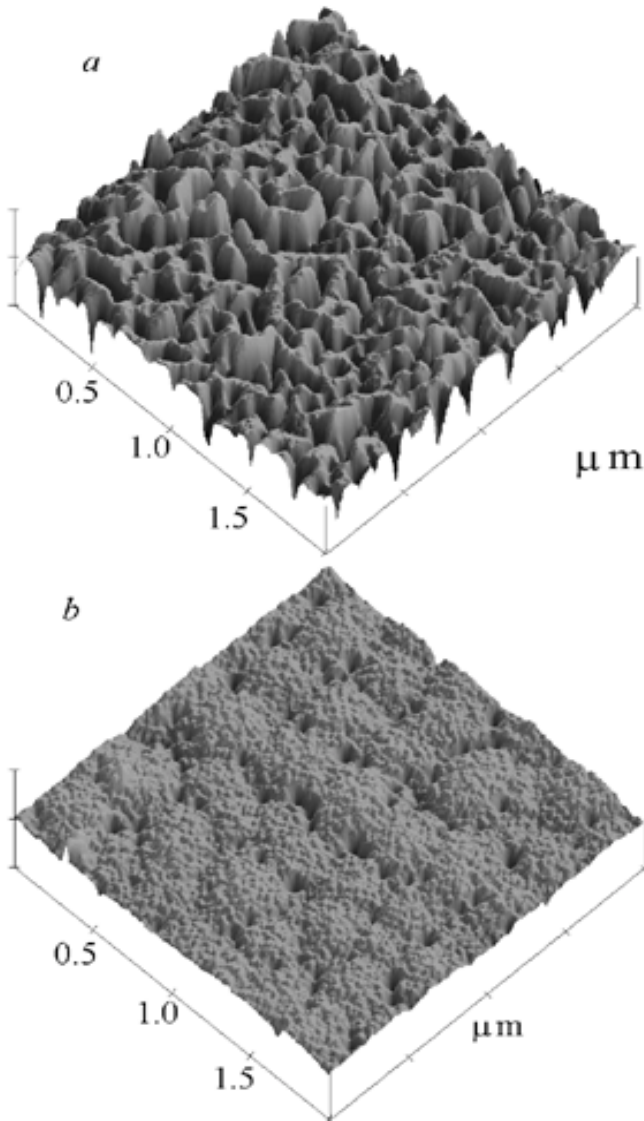


Fig 1. AFM images of sample #630 (a) and sample #632 (b)

400–500 nm. No such features are on the sample #630 surface. Its relief is formed by randomly located hollows and hills; their height spread is about  $\pm 10\text{--}12$  nm, while their size is 100–200 nm.

The mean square roughness of the sample #632 surface is 0.64 nm; that of sample #630 varies from 8.30 to 3.57 nm. The distribution of heights over surface is a Gauss-like curve. Its half-width is 2.51 nm (sample #632) and 5.7 nm (sample #630).

### C. Ellipsometry Measurements

Ellipsometry measurements have been used for investigation of composition and structure of Ge film surface.

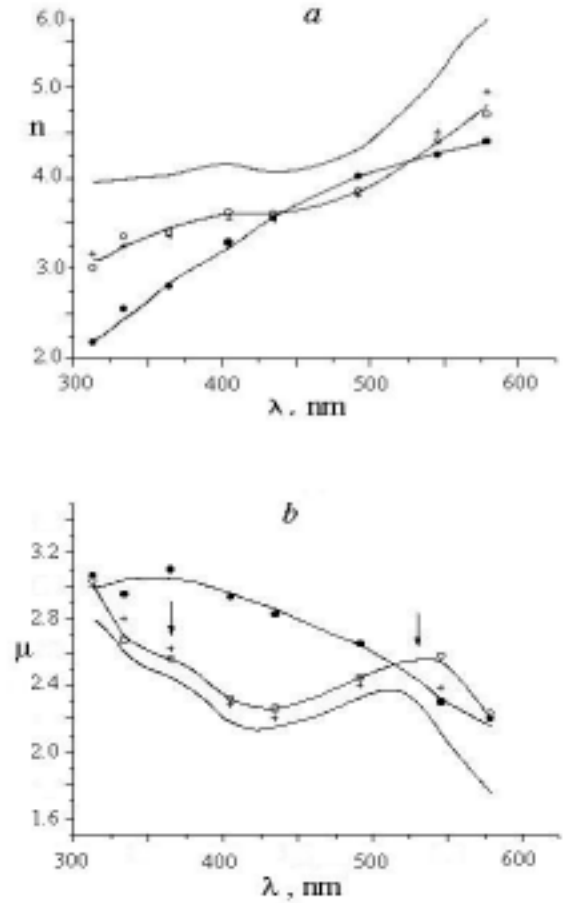


Fig.2. The refraction (a) and absorption (b) index vs light wavelength  $\lambda$  curves for single-crystalline (+), polycrystalline (o) and amorphous (•) films in comparison with published data (the curve without marks)

Ellipsometry is highly sensitive to the sample properties in the near-surface region. We determined the refractive and absorption indices of the Ge films, as well as the refractive index and thickness of the oxide layers on these films.

Ellipsometry measurements were performed using a version of Beattie photoelectric technique for eight lines of the mercury-discharge lamp emission (in the 313–579 nm spectral range), at different angles of light incidence onto the sample studied. We measured the ellipsometry parameters  $\cos\Delta$  and  $\tan\psi$ . Here  $\Delta$  is the phase difference between the orthogonal projections of the electric vector of light wave, and  $\tan\psi$  gives the ratio between reflection coefficients of these projections at a fixed angle of incidence. The Ge absorption coefficient in the above spectral range is about

$5 \times 10^{-5} \text{ cm}^{-1}$  (the probing beam penetration is about 20 nm), so the reflected light wave was formed near the surface of Ge film.

The thickness of oxide layer on the Ge film surface was reduced by etching in water solution of peroxide. To a first approximation (taking no account of a thin oxide layer on the Ge film surface), one can determine from the measured ellipsometry parameters two characteristics of the reflecting system, namely, refractive index  $n$  and absorption coefficient  $\mu$  of the Ge film.

Figure 2 represents typical spectral dependencies of optical constants for single-crystalline, polycrystalline and amorphous samples. For comparison similar dependencies for single-crystalline bulk Ge with oxide layer thickness less than 1–1.5 nm [5] are also given.

For the 313–579 nm wavelength range the spectra of optical constants for single-crystalline Ge are determined by electron transitions from valence into conduction bands (shown as vertical arrows in Fig. 2. The band structure (i.e., optical spectra) features are determined by the long-range crystalline order. Spectra of amorphous film differ essentially from those for crystalline germanium. Such transformation of optical spectra has been observed for amorphous Ge in [6]. It was due to absence of long-range order. The long-range crystalline order exists in individual crystallites of polycrystalline phase. So optical spectra of single-crystalline and polycrystalline samples will be similar in their principal features (Fig. 2). All the distinctions in the spectra of the films studied seem to result from variations of the oxide layer properties.

Calculation of the oxide layer parameters (thickness  $d$  and refractive index  $n_1$ ) has been made using the iteration routine [7]. The experimental values of  $\cos\Delta$  and  $\tan\psi$  related to different stages of surface cleaning depend on the oxide layer thickness. A starting point (i.e., the calculated  $\cos\Delta_0$  and  $\tan\psi_0$  values) had to be determined for which the experimental values of  $\cos\Delta$  and  $\tan\psi$  for different various degrees of surface cleaning corresponded to constant refractive index, and oxide thickness values coincided for different wavelengths. The starting point corresponds to zero thickness of the oxide layer and correctly reflects optical constants  $n$  and  $\mu$  of the Ge film. Then these optical constants were calculated from the  $\cos\Delta_0$  and  $\tan\psi_0$  values.

The calculated optical constants for single-crystalline and polycrystalline samples, as well as the oxide layer parameters, are given in Table II. The data for oxide layer are in good agreement with the published results for Ge dioxide  $\text{GeO}_2$ . Some excess of the refractive index of the oxide layer over the published value might be due to presence of unbound (unoxidized) germanium in the oxide film.

The oxide layer thickness depends on time of keeping in air and surface cleaning degree. Before

TABLE II  
OPTICAL PARAMETERS:-  
REFRACTIVE INDEX  $n$  AND ABSORPTION COEFFICIENT  $\mu$   
OF CRYSTALLINE Ge FILMS, AND OXIDE LAYER  
REFRACTIVE INDEX  $n_1$  AND THICKNESS  $d_1$  MEASURED AT  
DIFFERENT LIGHT WAVELENGTHS

$$\Delta n = 0.002, \Delta \mu = 0.04$$

$\lambda, \text{ nm}$	$n$	$\mu$	$n_1$	$d_1, \text{ nm}$
579	5.14	1.91	$1.82 \pm 0.1$	$2 \div 9.5$
546	4.88	2.10	$1.90 \pm 0.08$	$2 \div 9.6$
492	4.19	2.31	$1.87 \pm 0.07$	$2 \div 9.8$
435	3.994	2.07	$1.91 \pm 0.05$	$2.3 \div 9.2$
405	3.996	2.18	$1.98 \pm 0.04$	$2.1 \div 8.5$
365	3.984	2.53	$2.08 \pm 0.01$	$2.2 \div 9.5$
334	3.966	2.71	$2.01 \pm 0.05$	$2.2 \div 9.2$
313	3.922	2.98	$2.1 \pm 0.05$	$2.2 \div 9.2$

sample cleaning the oxide layer thickness was about 8–9.5 nm. It could be halved by etching in water solution of peroxide.

#### D. Galvanomagnetic Investigations

Figure 3 represents typical temperature dependencies of resistivity  $\rho$ , hole concentration  $p$  (determined from measurements of the Hall effect), Hall mobility  $\mu$  and magnetoresistance  $\Delta\rho/\rho$  for Ge films obtained with different degrees of structural perfection. The measurements were made in the 80–400 K temperature range and in magnetic fields up to 1.8 T. All the samples studied were of  $p$ -type.

The character of temperature dependencies of resistivity, Hall coefficient, Hall mobility and magnetoresistance depended on the structural perfection degree of the samples. For Ge films having polycrystalline structure the Hall coefficient practically did not depend on temperature at  $T < 250 \text{ }^\circ\text{C}$ . The hole concentration at room temperature was about  $10^{18} \text{ cm}^{-3}$ . The Hall mobility was as high as  $50 \text{ cm}^2/\text{V}\cdot\text{s}$  and decreased at cooling. At the same time magnetoresistance practically did not depend on temperature.

It is known [8] that transport phenomena in polycrystalline films are strongly influenced by intercrystalline boundaries. Conduction in polycrystalline films predominantly depends on intercrystalline boundaries, and the Hall coefficient depends on crystallites that have higher charge carrier concentration. This fact explains, in particular, essential distinction between the temperature dependencies of Hall mobility and magnetoresistance, as well as discrepancies in the hole mobility values obtained from the Hall effect and magnetoresistance measurements [8].

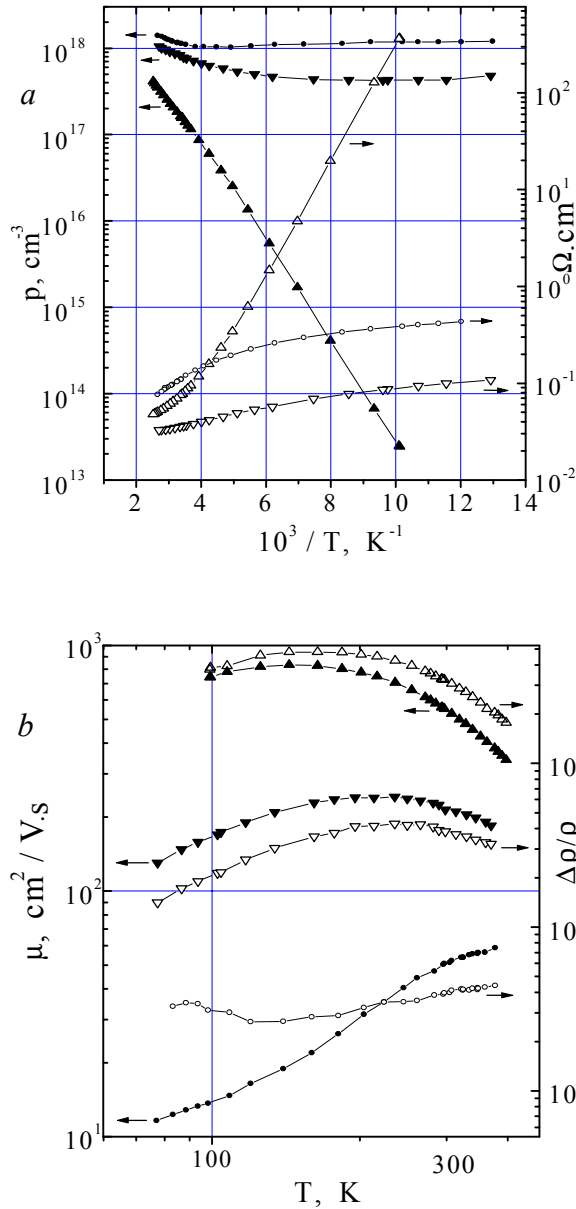


Fig 3. Charge carrier concentration (a), specific resistance (a), Hall mobility (b), magnetoresistance (b) of samples:  
 $\blacktriangle, \triangle$  - #449;  $\blacktriangledown, \triangledown$  - #632;  $\circ, \bullet$  - #630

The Ge films having mosaic single-crystalline (sample #632) and perfect single-crystalline structure (sample #449) are characterized by relatively high hole mobility. For single-crystalline  $p$ -Ge films the hole mobility can reach  $560 \text{ cm}^2/\text{V}\cdot\text{s}$  at room temperature. The charge carrier concentration determined from the Hall effect measurements at the same temperature is  $1.6 \times 10^{17} \text{ cm}^{-3}$ . The temperature dependencies of resistance and Hall coefficient for such films

are described by exponential law with constant activation energy  $E_1 = 0.12 \text{ eV}$  at  $T < 200 \text{ K}$ .

High value of conduction activation energy could be explained by strong compensation of Ge films [2]. Electrostatic potential fluctuations exist in heavily doped and strongly compensated semiconductors. They are related to randomly-nonuniform distribution of impurities [9]. The potential fluctuations modulate semiconductor band structure and change the charge carrier energy spectrum, thus resulting in appearance of state density "tails" in the gap. The electrical and optical effects in heavily doped and strongly compensated semiconductors are characterized by a number of features that are determined by the potential relief parameters. Conductivity in such semiconductors is determined by the percolation level  $E_p$ . One of the most pronounced manifestations of random field is the percolation conduction that is typical for semiconductors with large-scale potential relief [9].

Exponential temperature dependence of conductivity in heavily doped and strongly compensated Ge films is caused by thermal emission of charge carriers from the Fermi level  $E_F$  to the percolation level  $E_p$  and is characterized by the activation energy  $E_1 = E_p - E_F$ . The  $E_1$  value depends on the doping level and compensation degree [2], [9].

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