CHAOTIC POTENTIAL OF CHARGED DISLOCATIONS IN III-NITRIDE HETEROJUNCTIONS AT HIGH TEMPERATURES

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Abstract - *The paper investigates the high-temperature structure of the chaotic potential in heterojunctions of Group III nitrides, induced by the electrostatic field of charged dislocations. The amplitude of the chaotic potential in the junction plane was found taking into account the spatial dispersion of the dielectric response of two-dimensional electron gas. We have uncovered the dependence of the chaotic potential parameters on the parameters of the system. If two-dimensional non-degenerate gas is present in III-nitride heterojunctions, with the dislocation densities up to and over 10^{10} cm^{-2}, the magnitude of the chaotic potential amplitude exceeds that of the thermal energy..*

Introduction - *Heterojunctions based on nitrides of Group III elements (Al, Ga, In) are finding increasing applications in solid-state devices used as high-power microwave sources. While these systems offer a number of obvious advantages over the structures based on A_3B_5 compounds, certain drawbacks remain due to the specifics of the synthesis technology, affecting, for example, the parameters of high-electron-mobility transistors (HEMT). The parameter fluctuations detected for the devices are likely due to the initial defects in the materials and heterointerfaces forming. Lattice mismatch in III-nitrides and substrates used is known to generate initial misfit/threading dislocations, turning out to be electrically charged in many cases. Electron scattering by charged dislocations in the 2D channel of the HEMT produces a certain decrease in electron mobility. The chaotic potential causes tails to appear in the density of electronic states, with part of the carriers localized to the conducting channel in HEMT. The goal of this study consisted in determining the parameters of the chaotic potential of charged dislocations in heterojunctions of nitride semiconductor compounds at high temperatures.*

Results and discussion

Charged dislocation field

To be definite, we consider an indium-containing structure, InAlN/GaN, remaining stable at record high temperatures up to 1000 °C.

The magnitude of the field strength for a charged dislocation is obtained by a simple calculation in the form

$$F_i(\rho)=\frac{2\lambda}{\varepsilon}\left(\frac{1}{\rho}-\frac{1}{\sqrt{\rho^2+L_0^2}}\right)$$

Here ε is the dielectric constant of the medium where the ith dislocation is located, L_0 is the width of the space charge region.

Gives an estimate for the characteristic scale of the inhomogeneities in the surface field strength. The resulting function is monotonically decreasing, reaching its maximum at $R << L_0$.

$$\delta F(R)=\frac{4\lambda}{\varepsilon R}\sqrt{\pi N_{disl}}\left(R-\sqrt{R^2+L_0^2}+L_0\right)$$

Calculating the exact upper bound of this expression (in the limit $R \to 0$), we obtain the amplitude of the chaotic field:

$$\delta F=\frac{4\lambda\sqrt{\pi N_{disl}}}{\varepsilon}$$

Case of low density of electron states

The case when the densities of electron states in a heterojunction are relatively low deserves more detailed analysis of the potential fluctuations emerging, using the dielectric response function of the surface subsystem.
The dielectric response function has the following form in the high-temperature region (i.e., for classical statistics of two-dimensional electron gas):

$$\varepsilon(q)=\frac{\varepsilon_1+\varepsilon_2}{2}\cdot\left(1+\frac{q_s(q)}{q}\right)$$

Here ε_1 and ε_2 are the dielectric constants of contacting semiconductors, $q_s(q)$ is the screening parameter in a two-dimensional electronic system.
Allowing to repeat the previous calculation algorithm for directly finding the amplitude of the chaotic potential:

$$\delta U=\frac{\lambda kT}{en_s}\cdot\sqrt{\frac{N_{disl}}{\pi}}$$

Thus, to determine the magnitude of the chaotic potential amplitude, we should solve the transcendental equation obtained by substituting:

$$\delta U=\frac{\lambda}{eD_s}\cdot\sqrt{\frac{N_{disl}}{\pi}}\cdot exp\left[-\frac{\mu}{kT}-\frac{1}{2}\left(\frac{\delta U}{kT}\right)^2\right]$$

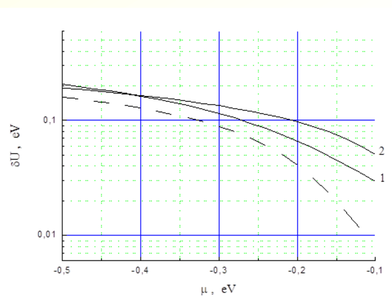

Fig. 1. Chaotic potential amplitude of charged dislocations (N_{disl} = 1010 cm^{-2}, λ = 0.01 ESU) in a III-nitride heterojunction for the surface state density $D_s \approx 10^{14}$ cm^{-2}eV^{-1} as a function of chemical potential for two temperatures: 600 K (1), 1200 K (2). The dashed curve corresponds to the δU(μ) dependence at $N_{disl} = 10^8$ cm^{-2} and T = 600 K

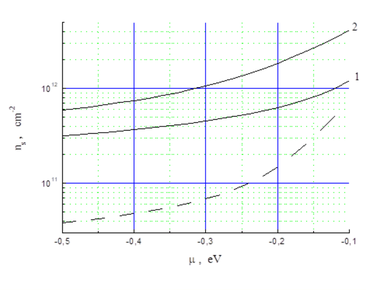

Fig. 2. Density of 2D electron gas in a III-nitride heterojunction for the surface state density $D_s \approx 10^{14}$ cm^{-2}eV^{-1} (the parameters of charged dislocations are $N_{disl} = 10^{10}$ cm^{-2}, λ = 0.01 ESU) as a function of the chemical potential for two temperatures: 600 K (1), 1200 K (2). The dashed curve corresponds to the ns(μ) dependence at $N_{disl} = 10^8$ cm^{-2} and T = 600 K.

Summary

Summarizing the analysis carried out, we should note that the expression for the characteristic values of surface potential inhomogeneity at high temperatures could be obtained from Eq. by substituting the density of states Ds with the ratio n⁄kT. Estimating the values that δU takes for the chaotic potential parameters in heterojunctions based on III-nitrides, we adopt the effective electron mass in the surface zone m* ≈ 0.2m (m is the electron rest mass) and the corresponding unperturbed density of surface states Ds ≈ 10^{14} cm^{-2}eV^{-1}. Then, assuming that the dislocation density at the interface is of the order of 10^{10} cm^{-2}, carrying the maximum charge per unit length of about 0.01 ESU, δU values in non-degenerate 2DEG exceed the thermal energies kT in a wide range of negative values of the chemical potential (or electrochemical potential, if a blocking voltage is applied to the transistor gate). The chaotic potential amplitude can reach over 100 meV in HEMP operating modes close to the cutoff, even at significantly lower dislocation densities. The corresponding 2DEG densities decrease from the initial levels (about 10^{13} cm^{-2}) by one or two orders of magnitude.