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Two-dimensional electron gas (2DEG) mobility affected by the in mole fraction fluctuation in $In_xAl_{1-x}N$/GaN heterostructures

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HIGHLIGHTS

- In mole fraction fluctuation scattering is calculated in InAlN/GaN heterostructure.
- We characterize the In mole fraction fluctuation with δx and Λ.
- The tendencies of mobility vs x are different for different value of Λ.

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ABSTRACT

In an $In_xAl_{1-x}N$/GaN heterostructure, we have studied the mobility limited by the In mole fraction fluctuation scattering. The In mole fraction fluctuation characterizes the quality of the $In_xAl_{1-x}N$ material with two parameters, one is the mole fraction fluctuation δx and the other is its lateral s Λ. Similar to a roughness scattering, for a fixed mole fraction x, the mobility limited by the In mole fraction fluctuation initially decreases with Λ increasing, reaches a minimum at a certain value of Λ and then increases.

1. Introduction

The $In_xAl_{1-x}N$ /GaN heterostructures have emerged recently as promising candidates for the next-generation electronic devices in millimeter-wave and submillimeter-wave applications [1–5]. The use of $In_xAl_{1-x}N$ layers offers several attractive advantages, such as a strong spontaneous polarization that induces an extremely high sheet carrier charge density in the two-dimensional electron gas (2DEG) [6] and a strain-free heterojunction that could reduce the structural defects caused by the lattice mismatch [7,8]. However, the $In_xAl_{1-x}N$ is an alloy known to be difficult to grow with high quality. Phase separation and composition inhomogeneity always occur in the $In_xAl_{1-x}N$ film [9]. The composition inhomogeneity of $In_xAl_{1-x}N$ will reduce the 2DEG mobility in the $In_xAl_{1-x}N$/GaN heterostructure. And the 2DEG mobility is an important electric parameter for $In_xAl_{1-x}N$ /GaN HEMT. In this paper, we will study the mobility limited by the In mole fraction fluctuation scattering which induced by the composition inhomogeneity in the $In_xAl_{1-x}N$ barrier for $In_xAl_{1-x}N$/GaN heterostructures.

2. Theory

Similar to the $Al_xGa_{1-x}N$/GaN heterostructures [10], the 2DEG sheet density exists at the interface between $In_xAl_{1-x}N$ barrier and GaN well is expressed as follow,

$$n_S(x) = \frac{\sigma(x)}{e} - \left(\frac{\epsilon_0\epsilon(x)}{Le^2}\right)\left[e\phi_b(x) + E_F(x) - \Delta E_C(x)\right] \quad (1)$$

where, σ is the sheet charge density caused by the total of spontaneous and piezoelectric polarizations, L is the $In_xAl_{1-x}N$ barrier thickness, ε_0 is the vacuum permittivity, $\varepsilon(x)$ is the relative dielectric constant, $e\phi_b(x)$ is the Schottky–Barrier height, here, we assume that $e\phi_b(x) = (3.15 - 3.7x)$ eV for Ni gate contact [12], $\Delta E_C(x)$ is conduction band offset at the interface between the $In_xAl_{1-x}N$ barrier and GaN well, $E_F(x)$ is the Fermi level with respect to the GaN, which can be obtained from

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$E_F(x) = E_0(x) + \frac{\pi\hbar^2}{m^*} n_S(x)$ with $E_0(x)$ being the ground energy level, and e is the electron charge.

For a triangle potential approach, the ground energy level for $In_xAl_{1-x}N$/GaN heterostructures is [13]

$$E_0(x) = \left\{ \frac{9\pi\hbar e^2}{8\varepsilon_0\sqrt{8m^*}} \frac{n_S(x)}{\varepsilon(x)} \right\}^{2/3} \tag{2}$$

where, $\hbar$ is the reduced Planck constant, $m^* \approx 0.22m_0$ is the effective electron mass of GaN with free electron mass m_0.

From Eq. (1), it is shown that the 2DEG sheet density is a function of the In mole fraction x in $In_xAl_{1-x}N$ barrier. The In mole fraction fluctuation which caused by the composition inhomogeneity in the growth progress is unable to be avoided. We assume that the composition is uniform along the growth axis, and the In mole fraction fluctuation $\delta x(r)$ parallel to the interface between the $In_xAl_{1-x}N$ barrier and GaN well can be characterized with a Gauss function, $\langle \delta x(r)\delta x(r') \rangle = (\delta x)^2 \exp\left(-\frac{|r-r'|^2}{\Lambda^2}\right)$ with δx being the In mole fraction fluctuation and Λ being its lateral size. Here, r respects to the position parallel to the interface. Due to the In mole fraction fluctuation along the interface, the 2DEG sheet density $n_s(x)$ will have a fluctuation in the same direction. From Eq. (2), the ground energy level will also have a fluctuation. The fluctuation of the ground energy level $\delta E_0(r)$ is expressed as follow

$$\delta E_0(r) = \frac{dE_0(r)}{dx}\delta x(r) = \frac{dE_0(r)}{dn_s}\frac{dn_s(r)}{dx}\delta x(r) \tag{3}$$

The ground energy level fluctuation $\delta E_0(r)$ will scatter the electrons moving in the GaN channel. The squared of the scattering matrix element and the relaxation time due to the In mole fraction fluctuation are given as follows

$$|M|^2 = \left(\frac{dE_0}{dn_S}\frac{dn_S}{dx}\right)^2 \pi(\delta x)^2\Lambda^2 \exp\left(-\frac{q^2\Lambda^2}{4}\right) \tag{4}$$

and

$$\frac{1}{\tau} = \frac{1}{(2\pi)^2}\left(\frac{2\pi}{\hbar}\right)\int \frac{|M|^2}{S(q)}(1 - \cos\theta)\delta(E_{k'} - E_k)d^2k' \tag{5}$$

Here, S (q) in Eq. (5) is the screen function, to a good approximation, it can be written as $S(q) = (1 + q_{TF}/q)^2$ [14], where $q_{TF} = 2\pi/a_B$ is the Thomas-Fermi wave vector with a_B being the effective Bohr radius of 2DEG, $\boldsymbol{q}$ is the scattering wave vector.

The mobility limited by the scattering due to the In mole fraction fluctuation is then given by

$$\mu = \frac{e}{m^*}\langle\tau\rangle \tag{6}$$

with $\langle\tau\rangle = \int \tau E \frac{\partial f(E)}{\partial E} dE \Big/ \int E \frac{\partial f_0(E)}{\partial E} dE$, and $f_0(E)$ is the Fermi–Dirac distribution function.

3. Results and discussion

The mobility limited by the scattering due to the In mole fraction fluctuation is influenced by the parameters which contain In mole fraction x, the amplitude of In mole fraction fluctuation δx, and its lateral size Λ. The $In_xAl_{1-x}N$ barrier thickness L will also affect the mobility through affecting the 2DEG sheet density.

The 2DEG sheet density exists at interface between $In_xAl_{1-x}N$ barrier and GaN well changes with In mole fraction x for different $In_xAl_{1-x}N$ barrier thickness L is given in Fig. 1(a). And it varies as a function of L is also given in Fig. 1(b). Here, the value x is chosen in the range from 0.05 to 0.25, which is around the value of In mole fraction making the lattice of $In_xAl_{1-x}N$ matches that of GaN. In

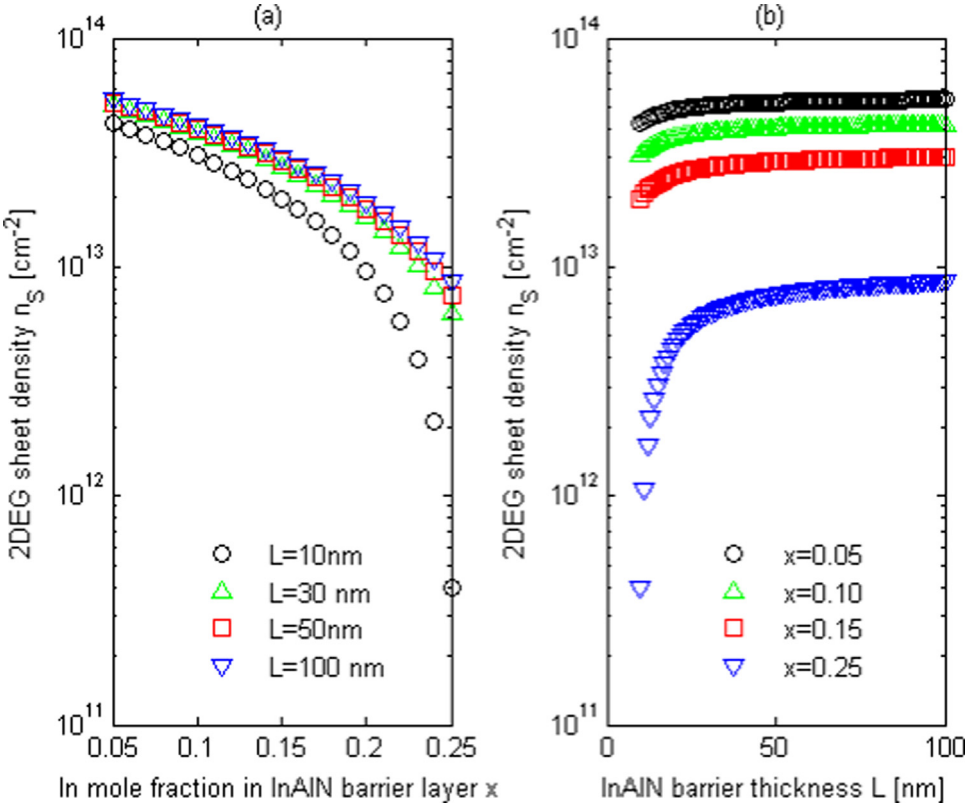

Fig. 1. 2DEG sheet density as a function of (a) In mole fraction x in InAlN, and (b) InAlN barrier thickness L.