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Electron Mobility of Two-dimensional Electron Gas in InGaN Heterostructures: Effects of Alloy Disorder and Random Dipole Scatterings

Tomoki Hoshino and Nobuya Mori

Graduate School of Engineering, Osaka University
2-1 Yamada-oka, Suita, Osaka 565-0871, Japan
Phone: +81-6-6879-7791 E-mail: {hoshino, mori}@si.eei.eng.osaka-u.ac.jp

Abstract

InGaN has a lighter electron effective-mass and is expected to be used as a channel material for high electron mobility transistors. However, it is an alloy semiconductor with a random distribution of the atoms, which introduces additional scattering mechanisms. In this work, the impact of the alloy disorder and random dipole scatterings on the electron mobility is theoretically investigated in InGaN heterostructures. The electron mobility is found to decrease significantly due to those alloy-induced scatterings.

1 Introduction

In AlGaN/GaN heterostructures, polarization charges create a highly-concentrated two-dimensional electron gas (2DEG) at the heterointerface. This enables us to realize a high electron mobility transistor (HEMT) for high frequency and high power devices. We can expect further improvement of the electron mobility by replacing the channel material with InGaN because of a lighter electron effective-mass. InGaN is, however, an alloy semiconductor with a random distribution of the atoms, which introduces additional scattering mechanisms. It is, therefore, unclear whether replacing the GaN-channel with InGaN can enhance the electron mobility. Here we investigate the impact of the alloy disorder and random dipole scatterings on the electron mobility in InGaN-channel HEMTs comparing with GaN-channel HEMTs, in which only the barrier layer consists of an alloy semiconductor.

2 Theory

The low-field electron mobility is calculated by performing single particle Monte Carlo simulation for GaN-channel and InGaN-channel HEMTs. The electronic states are calculated by self-consistently solving the coupled Schrödinger and Poisson equation, and the scattering rates are evaluated with the obtained electronic states. We include phonon (acoustic deformation and polar optical), alloy disorder, and random dipole scatterings.

In the self-consistent electronic states calculation, we use the 63:37 rule [1] for the conduction-band discontinuity, i.e. $\Delta E_c = 0.63\Delta E_g$, where ΔE_g is the band-gap difference. For the electron effective-mass in $In_xGa_{1-x}N$, we introduce a small bowing [2]:

$$m^*_{InGaN} = m^*_{InN}x + m^*_{GaN}(1-x) + bx(1-x) \quad (1)$$

with $m^*_{InN} = 0.07\,m_0$, $m^*_{GaN} = 0.2\,m_0$, and $b = -0.07\,m_0$.

The alloy disorder scattering rates are calculated with the alloy disorder potential $\Delta U = 1.5\,\mathrm{eV}$ [3] for AlGaN and 1.7 eV, the conduction-band discontinuity between InN and AlN, for InGaN. In the present study, we assume that the scattering potential is screened by the 2DEG [4]. For the random dipole scattering, we extend the method of Ref. [5] so that it can be applied for the case that the random dipoles exist in the channel [6].

3 Results and discussion

Figures 1 and 2 show the electronic states obtained by the self-consistent calculation for $Al_{0.27}Ga_{0.73}N$/GaN and $Al_{0.27}Ga_{0.73}N$/$In_{0.1}Ga_{0.9}N$/GaN, respectively. We see that the 2DEG is strongly confined in the InGaN-channel HEMT compared to the GaN-channel HEMT. This strong confinement in the InGaN-channel device leads to an increase in the phonon scattering rates.

Figure 3 shows the calculated 2DEG mobility, μ, as a function of the In mole fraction, x, of the channel. Note that the marks at $x = 0$ represent the results for the GaN-channel HEMT. When we ignore both alloy disorder and random dipole scatterings (open circles), μ is slightly improved as x increases. Although the effective-mass becomes lighter as x increases, the phonon scattering rates increase in the InGaN-channel HEMT, which results in a slight increase in the phonon-limited μ of the InGaN-channel HEMT. Closed (open) squares show μ including phonon and alloy disorder (random dipole) scatterings; Closed circles shows μ including phonon, alloy disorder, and random dipole scatterings. For the GaN-channel HEMT, alloy disorder and random dipole scatterings have a little impact on μ. This is because only the barrier consists of an alloy semiconductor. The effect

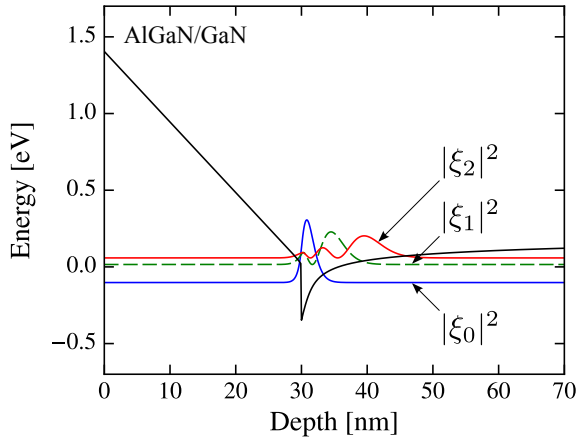

Fig. 1: Conduction band edge and spatial probability distribution $|\xi_i|^2$ of $Al_{0.27}Ga_{0.73}N$/GaN heterostructure.

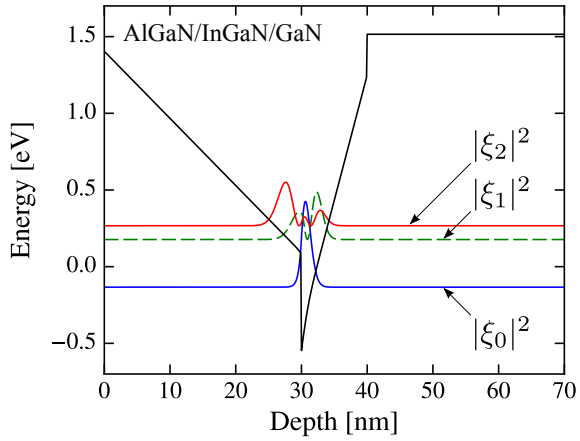

Fig. 2: The same as Fig. 1 but for $Al_{0.27}Ga_{0.73}N/In_{0.1}Ga_{0.9}N$/GaN heterostructure.

of the random dipole scattering is larger than that of the alloy disorder scattering. This may be attributed to the short-range nature of the alloy disorder scattering. For the InGaN-channel HEMT, however, alloy disorder and dipole scatterings have a strong impact and μ decreases significantly as x increases.

Figure 4 shows μ as a function of the InGaN channel thickness w. Note that the marks at $w = 0$ nm represent the results for the GaN-channel HEMT. We find that the mobility suddenly decreases as w increases from 0 nm, and w dependence of μ is weak for $w > 1$ nm. This behavior can be understood by considerting the fact that the 2DEG is strongly confined in the InGaN layer.

4 Conclusions

We investigated the impact of the alloy disorder and random dipole scatterings on the 2DEG mobility, μ, in InGaN-channel HEMTs comparing with GaN-channel HEMTs. We find that μ decreases significantly as the In

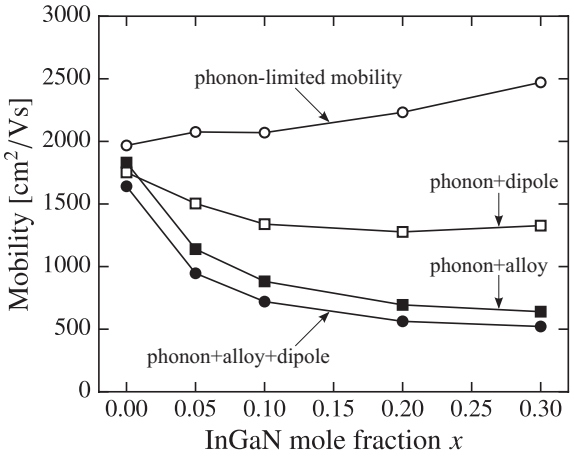

Fig. 3: 2DEG mobility as a function of the InGaN mole fraction for the InGaN channel thickness of 10 nm. Open circles represent the phonon-limited mobility. Closed (open) squares show the mobility including phonon and alloy disorder (random dipole). Closed circles represent the mobility including phonon, alloy disorder, and random dipole.

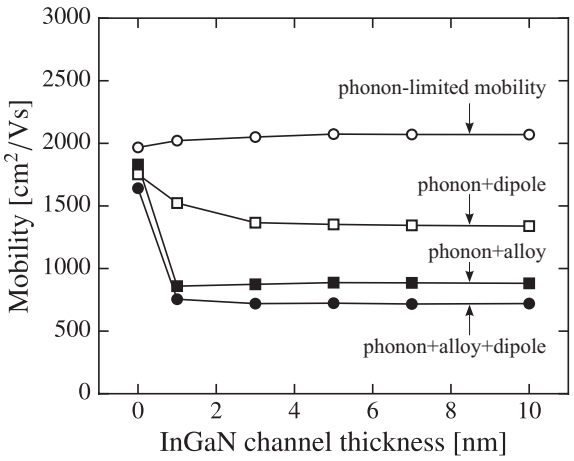

Fig. 4: 2DEG mobility as a function of the InGaN channel thickness for the In mole fraction $x = 0.1$. The symbols are the same as used in Fig. 3.

mole fraction increases. We also find that μ suddenly decreases when we insert a thin InGaN layer of thickness $w = 1$ nm and w dependence of μ is weak for $w > 1$ nm.

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