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Electron transport in AlGaN/GaN HEMTs using a strain model

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ABSTRACT

The electron transport in AlGaN/GaN HEMTs was investigated using the strain model by Sentaurus TCAD simulations. The impact of strain variations on electron transport properties was studied. The adjustment of strain is achieved by changing strained lattice constant (a) and the strain relaxation (R) in AlGaN layer based on strain model, and then the relationship between piezoelectric polarization and strain values is discussed. The results show that an external tensile strain in AlGaN layer has a strong influence on the distribution and concentration of 2DEG located close to the AlGaN/GaN interface. Meanwhile the threshold voltage and saturated drain current are proportional to the strain values, and the breakdown voltage is improved due to the adjustment of strain. Furthermore, the change of electron transport was also investigated by decreasing the local strain near the gate edge in AlGaN layer. It can be founded that the surface electric field becomes more uniform and the breakdown voltage is enhanced. The results based on the relation between strain and electron transport are beneficial to regulate the electrical properties in AlGaN/GaN HEMTs.

1. Introduction

In recent years, researches on AlGaN/GaN high electron mobility transistors (HEMTs) have received much attention due to their excellent electrical properties [1–3]. They are attractive candidates for high switching frequency, high breakdown voltage and high power. The two-dimensional electron gas (2DEG) induced by spontaneous and piezoelectric polarization is formed near the interface of AlGaN/GaN heterostructures. The polarization induced sheet charge bound at the AlGaN/GaN interfaces changes with different strain values [4], and the electron transport properties are sensitive to the variations of strain. Moreover, the strain in heterostructures can be defined by variations of strained lattice constant. Also, the electron transport properties of 2DEG can be improved by the increase of Al content in the AlGaN barrier layer. While the increase of Al content will cause undesired strain relaxation of the AlGaN barrier layer. Thus, the 2DEG which increases with the increasing of Al content is limited by strain relaxation. The resulting strains are really important for electron transport properties within the devices [5–7].

Dependence of the concentration and distribution of 2DEG on piezoelectric effect in strained heterostructures was reported previously [8–10]. And this effect is shown to have a strong influence on 2DEG electron density. For Ga-faced AlGaN/GaN HEMTs with the direct piezoelectric effect, an external tensile strain will lead to the increase of 2DEG concentration. This is further emphasized in pseudomophic, wurzite AlGaN/GaN heterostructures, where the piezoelectric polarization of the strained AlGaN barrier layer is more than five times that of AlGaAs/GaAs structures. In addition, it was reported that strain in pseadomorphically grown AlGaN/GaN heterostructures can cause additional piezoelectric field of about 2 MV/cm [11–13]. There is relevant relation between strain and polarization, and the density of 2DEG can be increased by polarization induced electric field. Although the electron mobility also relies on the strain [14], the change of mobility caused by strain is negligible compared to the change of 2DEG density by strain [15]. Despite researches on strain and polarization in AlGaN/GaN heterostructures reported, most of works focus on the influence on polarization induced charge while there is lack of comprehensive investigation on relationship between strain and the electron transport properties in AlGaN/GaN HEMTs. Furthermore, the progress in understanding the relationship is limited by the difficulties of measuring strain values in experiments [16].

In this work, we will focus on the effect of strain in AlGaN barrier layer on the electron transport properties in AlGaN/GaN HEMT using a strain model. The change of electrical properties induced by stain will be shown. The variation of strain in AlGaN/GaN heterostructures is carried out by adjusting strained lattice constant and strain relaxation, and the dependence of threshold voltage and saturated drain current on strain values is studied using

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Sentaurus TCAD. In addition, the local strain will be adjusted and investigated in order to improve breakdown voltage.

2. Device structure and mechanism

The schematic cross-section of the simulated, unintentionally-doped (UID), asymmetrical, 1.5-µm gate length AlGaN/GaN HEMT with a gate width of 1 µm is presented in Fig. 1(a). And the width of the whole device is 1 µm. The gate-to-source and gate-to-drain spacings are 2 µm and 5 µm, respectively. Also, the AlGaN/GaN HEMT consists of 0.2-µm-thick Si_3N_4 passivation layer, a 20-nm-thick AlGaN layer, a 20-nm-thick GaN channel and a 2.5-µm-thick GaN layer. With Si_3N_4 passivation layer, the surface state of AlGaN barrier can be improved thus suppressing the current collapse phenomenon. The wurtzite phase of GaN with Ga-face is used to take into account polarization effects in the AlGaN/GaN HEMT due to its higher electron mobility than that with N-face [17]. In our simulations, the Al content (x) of AlGaN is a constant, and it's set as 0.26. The x and y direction are given.

Two dimensional electron gases depend both on piezoelectric and spontaneous polarization. The relation between strain and polarization in AlGaN/GaN heterostructures was investigated [11], and the strain model based the relation was established. Then, the schematic diagram of theoretical relationship between strain value and electron transport properties was given in Fig. 2, which can help us to have an explicit physics image about the strain model. It has been reported that piezoelectric polarization can exert a substantial influence on the concentration of 2DEG in stained AlGaN/GaN heterostructures. AlN, GaN belongs to the wurtzite group-III nitrides, and they are tetrahedrally coordinated semiconductors with a hexagonal Bravais lattice. Its crystal lattice structure can be determined by the height c_0 of the prism and the hexagonal edge $\boldsymbol{a_0}$, and a microscopic dimensionless parameter u, which is defined as the length of the bond parallel to the c axis. The in-plane strain along the interface can be defined by

$$\varepsilon_x = \varepsilon_y = \frac{a - a_0}{a_0}, \tag{1}$$

where a represents strained lattice constant, $\boldsymbol{a_0}$ is unstrained lattice constant.

And the strain along the c axis is given by

$$\varepsilon_z = \frac{c - c_0}{c_0}, \tag{2}$$

where c represents strained lattice constant along the c axis, c_0 is unstrained lattice constant along the c axis.

For strained AlGaN/GaN layers grown in the (0001) orientation [see Fig. 1(b)], the relationship betweenP_{PE} and strain is given by

$$P_{\mathrm{PE}} = e_{33}\varepsilon_z + e_{31}(\varepsilon_x + \varepsilon_y), \tag{3}$$

where e_{33}, e_{31} are the piezoelectric coefficients. And the relation between the lattice constants in the hexagonal AlGaN system is given by

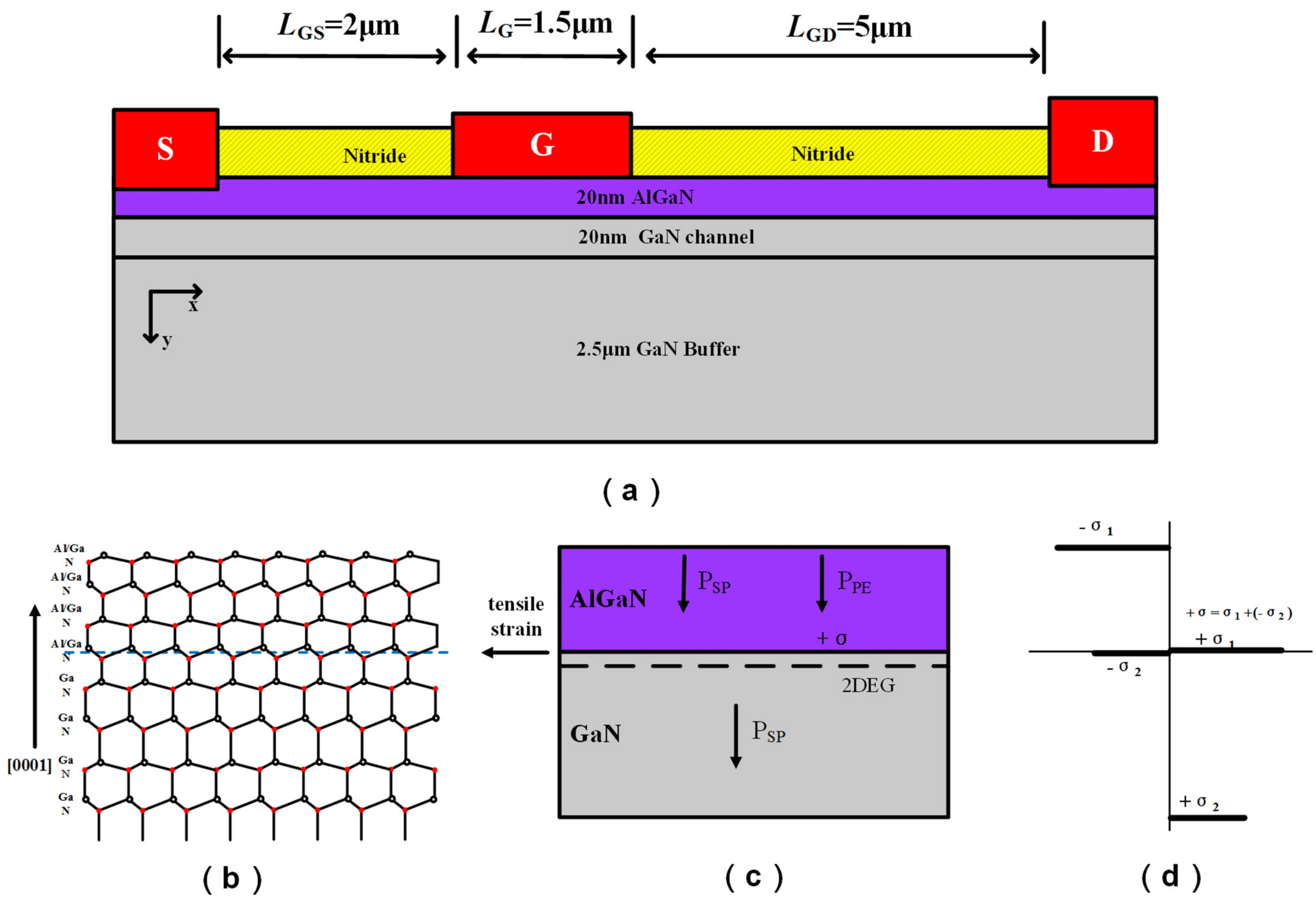

Fig. 1. (a) Schematic cross-section of the simulation AlGaN/GaN HEMT. This is a conventional structure called normally-on HEMT. (b) The crystal structure of strained AlGaN/GaN heterostructures, and there is a tensile strain in AlGaN layer. The wurtzite phase of GaN with Ga-face is used during simulation. (c) Spontaneous and piezoelectric polarization in AlGaN/GaN heterostructures with Ga-face polarity. The orientation of spontaneous and piezoelectric polarization is shown, and 2DEG located close to AlGaN/GaN interface is induced by polarization charge. (d) Schematic diagram of polarization charge distribution. The net polarization induced charge ($+\sigma = +\sigma_1 - \sigma_2$) located in AlGaN/GaN interface.