RF LOSS IMPROVEMENT OF GAN-HEMTS GROWN ON SILICON BY REDUCTION OF THE INVERSION CHANNEL AT SI INTERFACE

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Regarding the unique characteristics (high breakdown field, high power density, high efficiency, and broadband) GaN are now broadly recognized as a key technology for many applications. In particular, GaN-based HEMTs are able to operate at high power, high frequencies and high temperatures, exhibiting various excellent characteristics superior to those of conventional Si-based semiconductors. GaN-HEMTs on Si technology is expected to drastically reduce the fabrication cost. However, one of the main issues is the parasitic loss that can adversely impact the RF device performances. A free-electron inversion channel, which is caused by the positive piezoelectric charge at the AlN/Si interface induced by the piezoelectric field in the tensile AlN grown on Si, plays a critical role in the RF losses. An adoption of a low-temperature AlN near Si interface induces an unintentionally carbon-doped layer acting as a negatively fixed charge layer that is able to compensate for positive piezoelectric charge resulting in the improvements of both the RF losses and the leakage.

1 Introduction For GaN-based HEMTs on Si, it was widely believed that the RF parasitic loss was due to the low resistivity of Si substrate and the interfacial p-type-doped layer, which mainly related to Ga and/or Al diffusion into the Si substrate [1]. A free-electron inversion layer at the AlN/Si interface, which limits the breakdown voltage of GaN-HEMT on Si, has been proven in [2]. However, the impact of the electron inversion layer on RF loss of GaN-HEMTs on Si haven't been studied yet.

In this paper, we have discussed the RF losses mechanism in GaN-HEMT/Si, which relates to the inversion channel, induced by the piezoelectric field in AlN buffer.

2 Experimental The epitaxial growth of the AlGaN/GaN HEMT has been achieved by MOCVD either on high-resistivity (HR) Si(111) (R = 10,000 Ohm.cm) or on low-resistivity (LR) Si(111) (R = 80 Ohm.cm). The GaN-HEMT structure described in this study consists of an AlN buffer layer (with different thickness: ~100 and ~ 200 nm), a three step-graded AlGaN transition layer, a ~1200 nm GaN layer, and a ~20 nm $Al_{0.2}Ga_{0.8}N$ barrier layer.

Measuring the RF losses on CPW lines in function of the frequencies is a straightforward manner to identify and quantify RF loss phenomena. Therefore, we have characterized this effect by measuring transmission line losses in CPWs deposited on the buffer layers and GaN-HEMT/Si

The films were characterized using a High Resolution X-ray (HRXRD), Raman spectroscopy, Scan electron microscopy (SEM), and Secondary ion mass spectrometry (SIMS).

3 Results and discussion In figure 1, the RF loss of a CPW on AlN/Si drastically increases as increasing the thickness of AlN buffer from 100 nm to 200 nm, even at very low frequency (250 MHz). It indicates that there exists a highly conductive loss channel, which become a dominant loss factor at low frequencies.

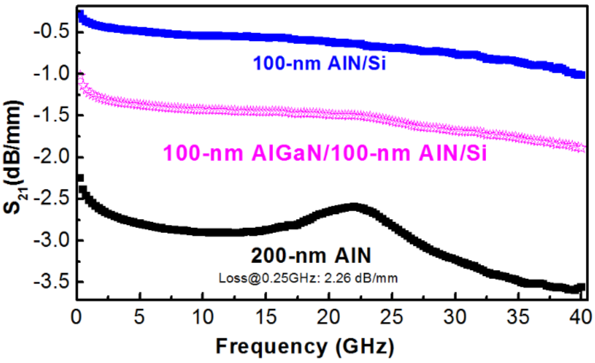

Figure 1 The RF Losses of CPWs on 100-nm AlN/Si, 200-nm AlN/Si, as well as 100-nm AlGaN/100-nm AlN/Si

As we know, AlN is piezoelectric material, the large tensile stress induced by mismatch between AlN and Si results in a sheet positive piezoelectric charge at the AlN/Si interface (fig. 2). It causes the formation of a potential well which confines carriers to a region close to the interface to form a two dimensional electron gas (2DEG). The electrons in the 2DEG channel exhibit much higher mobility than those in the bulk. Because of above process, the conductivity of the two-dimensional electron gas (2DEG) depends on the strength of the piezoelectric field, donor surface state, and Fermi energy level (E_F); correspondingly AlN thickness, and doping level in Si and AlN.

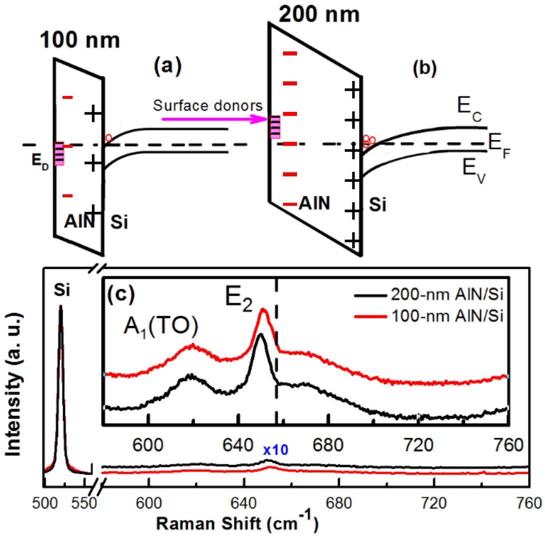

Figure 2 Schematic energy band diagrams of 100-nm AlN/Si (a) and 200-nm AlN/Si (b) showing the formation of a two dimensional electron gas (2DEG) at AlN/Si. Raman spectra of 100-nm AlN/Si (red) and of 200-nm AlN/Si (black) (b), the dash line shows the E_2 mode of AlN bulk single crystal [3].

Fig. 2c shows Raman spectra of 100-nm AlN/Si (red) and of 200-nm AlN/Si (black). As can be seen, the E_2 mode of 200-nm AlN/Si at 649.9 cm^{-1} is lower than the E_2 mode of 100-nm AlN/Si at 651.3 cm^{-1} that indicates a higher biaxial stress in the thicker AlN buffer/Si. The higher biaxial stress results in the stronger polarization field. Consequently, the RF losses in CPW lying on AlN/Si drastically increases as increasing the AlN thickness.

Indeed, the AlN/Si-interfacial loss, which depends strongly on the thickness of AlN, becomes a dominant loss factor compared to conductor (lines), dielectric (AlN) or substrate losses. Thus, it is essential to minimize the AlN thickness to reduce the interfacial RF loss.

However, it conversely degrades the crystallinity of subsequent GaN and increases leakage current. Therefore, to optimize a GaN-HEMT structure on Si, it requires to take into account such trade-off. Our previous works have reported that using a multilayer High-Low-High Temperature (HLH) AlN buffer layer inducing an unintentionally rich carbon-doped layer resulted in an improvement in quality of GaN epitaxial layer on Si; as well as enhanced the DC performance GaN-HEMTs [4-6]. SIMs and C-V measurement results show the unintentionally carbon-doped layer acting as a negatively fixed charge layer, which is able to compensate for positive piezoelectric charge, resulting in the reduction of the inversion layer at AlN/Si interface and the consequent improvement of RF loss (fig. 3).

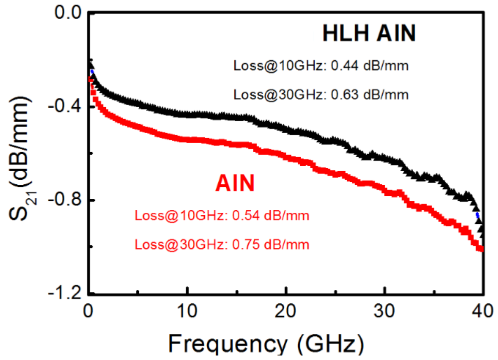

Figure 3 The Losses of CPW on AlN/Si (red) and on HLH AlN/Si (black).

Lastly the comparison between the losses of CPW deposited on mesa floor of GaN-HEMT on HR Si and on LR Si with different buffer layers also proves the strong improvement of the RF loss by the reduction of the inversion layer.

4 Conclusions Due to residual stress in AlN buffer, there exists a conductive inversion channel at interface, which plays a very important role in RF losses of GaN-HEMT on Si. Understanding the loss mechanisms of GaN-HEMT/Si will undoubtedly help to optimize epitaxial growth structure for further improving the overall device RF performance. We have demonstrated that using a fixed negative charge layer near the interface will help to suppress the electrons inversion layer.

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References

[1] H. Shinichi, I. Masanori, M. Toshiharu, O. Hideyuki, M. Yoshiaki, T. Isao, et al., Appl. Phys. Express **2**, 061001 (2009).

[2] D. Visalli, M. Van Hove, P. Srivastava, J. Derluyn, J. Das, M. Leys, et al., Appl. Phys. Lett. 97 (2010) 113501.

[3] W. Zheng, R. Zheng, F. Huang, H. Wu, and F. Li, Photonics Res. **3**, 38 (2015).

[4] K.-L. Lin, E.-Y. Chang, Y.-L. Hsiao, W.-C. Huang, T. Li, D. Tweet, et al., Appl. Phys. Lett. **91**, 22211 (2007).

[5] H. Yu-Lin, L. Lung-Chi, W. Chia-Hsun, C. Edward Yi, I. K. Chien, M. Jer-Shen, et al., Jpn. J. Appl. Phys. **51**, 025505 (2012).

[6] T. T. Luong, Y. T. Ho, B. T. Tran, Y. Y. Woong, and E. Y. Chang, Chem. Vap. Deposition **21**, 33 (2015).