Influence of a thick nitride layer on transmission loss in GaN-on-3C-SiC/low resistivity Si

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Abstract We report the effect of a thick nitride layer on transmission loss in GaN-on-3C-SiC/low resistivity Si (LR-Si). Microstrip lines of finite length and width with ground pads were fabricated on three GaN-on-3C-SiC/LR-Si epitaxial structures with varying nitride layer thicknesses of 3.2, 5.3, and 8.0 µm. The loss performance of microstrip lines on different substrates was evaluated in the frequency range of 0.1 to 9 GHz. The sample with 8.0 µm thick nitride layer showed a minimal loss of 0.3 dB/mm at 9 GHz compared to the other samples. The evaluated data from electromagnetic (EM) simulation also confirmed a decreasing trend of loss with increasing nitride layer thickness. Temperature dependent loss evaluation also verified the above fact.

key words: GaN-on-3C-SiC/LR-Si, thick nitride layer, microstrip lines, attenuation, temperature

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

The GaN-based devices offer excellent superiority in high-power and high-frequency technologies because of their capability to deliver high power densities at both microwave and millimeter-wave (mmW) frequencies along with high electron saturation velocities [1–11]. For GaN-based RF power devices, SiC is usually preferable owing to high thermal conductivity, high electrical resistivity, and very low mismatch to GaN [12–15]. However, SiC substrates are expensive and unavailable in large size wafers, which limits the cost-effective scaling of the technology [16–18]. On the other hand, GaN-on-Si technology provides better economical viability in commercial applications as they are widely available in cost-effective large size wafers [19, 20].

Regarding RF performance of GaN-based devices, three main losses that contribute to total RF loss are dielectric loss in the substrate, conductor loss, and radiation loss [21]. In the case of GaN-on-Si technology, high resistivity Si (HR-Si) substrate showed improved performance by reducing the substrate loss [22–24]. However, at high temperatures, charge carriers generate in HR-Si which results in reduced resistivity and increased substrate loss [25, 26]. In addition, the manufacturing cost of GaN-on-HR-Si is higher than GaN-on-LR-Si technology [27].

With increasing development and interest in GaN-on-Si-based RF technology, the influence of epitaxial structure on RF loss becomes a crucial factor. However, there are no such reports on the effect of nitride layer thickness on the frequency response of transmission loss in GaN-on-3C-SiC/LR-Si. In our previous work, it was reported that a GaN-on-3C-SiC/LR-Si structure with a thick nitride layer exhibits very low RF loss by eliminating the low resistivity of Si and also provides better thermal stability [28, 29]. However, the characterization of RF loss on metal pads is not sufficient to successfully establish the effect of thick nitride layer on the frequency response of total RF loss.

In this paper, we used three different epi-structures with varying nitride layer thickness for a deeper understanding about the substrate RF loss. From the S-parameter measurements and EM simulated data, it was observed that the sample with the thickest nitride layer of 8.0 µm showed the minimal RF loss, whereas the loss was almost doubled for the sample with a 3.2 µm thick nitride layer. The temperature dependent study also confirmed the above observation.

2. Design and fabrication of microstrip line

The schematic cross-sectional structure of designed and fabricated transmission lines on three different GaN-on-3C-SiC/Si epitaxial structures (denoted by samples A, B, and C) is shown in Fig. 1, where only the nitride layer thicknesses were varied.

The GaN-on-3C-SiC/Si epitaxial structures (from top to bottom) consist of a GaN layer, an III-N buffer layer followed by a 1 µm thick 3C-SiC on a 1 mm thick LR-Si substrate. The combined thickness of the GaN and III-N buffer layer is termed as the total nitride layer (as shown in Fig. 1), which is 3.2, 5.3, and 8.0 µm for samples A, B, and C, respectively. For the fabrication of GaN-on-3C-SiC/Si and to maintain
the equivalency of an actual HEMT device, initially, Al-GaN/GaN heterostructures were grown by metal organic chemical vapor deposition (MOCVD) on commercially prepared 1 μm thick 3C-SiC(111)/low resistive (≤ 3.0 mΩ-cm) Si substrate with a 6-inch diameter. After epitaxial growth, we confirmed crack-free, high-quality nitride layers on Si. To fabricate the transmission lines, the conducting AlGaN layer was fully removed using the BCl₃ plasma-based reactive ion etching (RIE). Transmission lines with a length (L) of 180 μm and a width (W) of 120 μm were fabricated. For the GSG probe connection, wide ground plates of 200 μm were fabricated at both sides of the signal line keeping a gap of 70 μm from the signal line. For metallization purpose, a total 0.25 μm thick metal stack (T) of Ti/Au (50/200 nm) was deposited using the electron beam evaporation technique. No backside ground plane was fabricated in all the samples, thus the metal stage acts as the ground. While designing the transmission lines, it seemed that there exists a virtual ground close to the interface of 3C-SiC and LR-Si substrate, as shown with a yellow dotted line in Fig. 1. As a result, the distance between the signal line and virtual ground plane becomes almost the same as the thickness of epitaxial structure on Si substrate. Consequently, the gap between the signal line and ground plates does not affect the transmission line characteristics. Thus, these transmission lines work as microstrip lines.

3. Results and discussion

The performance of the fabricated microstrip lines was characterized with a vector network analyzer to measure the S-parameters in the frequency range of 0.1 to 9 GHz. The system was precisely calibrated with the open-short-load-through calibration standard. To estimate the transmission loss, attenuation constants of all the samples were calculated from the S-parameters using Eq. 1.

\[ e^{-\gamma L} = \frac{2S_{21}}{1 - S_{11}^2 + S_{21}^2 \pm \sqrt{(1 + S_{11}^2 - S_{21}^2)^2 - 4S_{11}^2 S_{21}^2}} \]  \hspace{1cm} (1)

where \( \gamma \) is the propagation constant, represented as \( \gamma = \alpha + j\beta \) \([30,31]\). The real part of \( \gamma \) is considered as the attenuation constant (\( \alpha \)) and \( L \) is the length of the microstrip line.

In Fig. 2, the measured attenuation constants of fabricated microstrip lines on samples A, B, and C are represented (the colored solid lines). At 9 GHz, the measured loss of samples A, B, and C were 0.61, 0.42, and 0.3 dB/mm, respectively. From the results, it can be seen that loss was decreased with increasing nitride layer thickness. The transmission loss was almost doubled for sample A compared to sample C while for sample B, it remained in between. Considering a lumped element equivalent circuit model of a microstrip line on GaN-on-Si structure, there exists a series combination of nitride layer capacitance (\( C_{\text{nitride}} \)) and underlying parallelly connected capacitance (\( C_{\text{Si}} \)) and resistance (\( R_{\text{Si}} \)) of the Si substrate \([32]\). The distance between the signal line and virtual ground plane in the Si substrate is longest in sample C because of the thickest GaN layer. Hence, following the inversely proportional relationship of capacitance and distance, the \( C_{\text{nitride}} \) is lowest in sample C and highest in sample A. Because of that, with the 8.0 μm thick nitride layer (for sample C), the effect of lossy capacitance \( C_{\text{Si}} \) is smaller than samples with 3.2 and 5.3 μm nitride layer (for samples A and B, respectively). As a result, the loss was reduced with a thick GaN layer.

In addition, the influence of thick nitride layer on RF transmission loss was analyzed by EM simulation in Keysight ADS momentum. To evaluate the effect of nitride layer thickness, we used the same substrate parameters for all samples only by varying the thickness. The epitaxial layers on 3C-SiC/Si were treated as a single equivalent nitride layer with a uniform permittivity of 10.0 and a dielectric loss tangent of 0.1. The dimensions of the microstrip lines and metal thickness used in EM simulation were the same as the fabricated parameters. Hence, the EM simulation result only shows the influence of nitride layer thickness on transmission loss. Figs. 3a and 3b represent the S-parameters evaluated from both the EM simulation and measurement data for sample...
Temperature dependent loss evaluation of microstrip lines in GaN-on-3C-SiC/LR-Si substrate. The evaluation of loss performance exhibited that with increasing nitride layer thickness, RF loss gradually decreases. As a result, the sample with an 8.0 μm thick nitride layer showed the minimal loss of 0.3 dB/mm compared to the sample with a 3.2 μm thick nitride layer, which showed almost double attenuation of 0.61 dB/mm at the same frequency of 9 GHz. Moreover, the EM simulation result of all samples confirmed the above observation. Furthermore, temperature dependent loss evaluation of the sample with the thickest nitride layer also exhibited excellent temperature stability at both frequencies of 2 and 9 GHz. Hence, an introduction of a thick nitride layer of 8.0 μm in GaN-on-3C-SiC/LR-Si can successfully minimize the RF loss compared to the same epitaxial structure with a thin nitride layer. Therefore, the above structure can be a very promising candidate for future cost-effective GaN-on-Si RF technologies.

4. Summary

In summary, we report an improvement of transmission loss in GaN-on-3C-SiC/LR-Si substrates by introducing a thick nitride layer. The same epitaxial structure of GaN on 3C-SiC/Si with three different nitride layer thicknesses of 3.2, 5.3, and 8.0 μm were used. The evaluation of loss performance exhibited that with increasing nitride layer thickness, RF loss gradually decreases. As a result, the sample with an 8.0 μm thick nitride layer achieved a thermally stable amplifier performance [28, 29]. Therefore, it can be confirmed that a thick nitride layer on GaN-on-3C-SiC/LR-Si can effectively minimize transmission loss.

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