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MMIC LNA based novel composite-channel $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N/GaN$ HEMTs*

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A microwave monolithic integrated circuit (MMIC) C-band low noise amplifier (LNA) using 1 μm-gate composite-channel $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N/GaN$ high electron mobility transistors (CC-HEMTs) has been designed, fabricated and characterized. The material structure and special channel of CC-HEMT were given and analysed. The MMIC LNA with CC-HEMT showed a noise figure of 2.4 dB, an associated gain of 12.3 dB, an input return loss of –6 dB and an output return loss of –16 dB at 6 GHz. The IIP3 of the LNA is 13 dBm at 6 GHz. The LNA with 1 μm × 100 μm device showed very high-dynamic range with decent gain and noise figure.

Keywords: slow noise amplifier, composite-channel AlGaN/GaN HEMTs, linearity
PACC: 7280E, 7125R

1. Introduction

As the third typical semiconductor material, GaN has been widely investigated for several years due to their high breakdown field, high saturation velocity. GaN high electron mobility transistors (HEMTs) emerge as the promising candidates for next generation wireless communication.[1,2] Superior results have been reported in microwave power performance of AlGaN/GaN HEMTs,[3−5] due to the great progress made in material preparation and device fabrication techniques. Meanwhile, excellent microwave noise performances of AlGaN/GaN HEMTs have been reported.[6−8] The low noise amplifier (LNA) based on GaN HEMT with high breakdown voltage was used in front-ends of receiver to eliminate the need for extra RF limiting circuitry, which degrades the noise performance of the LNA and receiver system. Recently, a few monolithic LNAs have been reported, which employed conventional AlGaN/GaN HEMTs.[9−13] This paper reports a microwave monolithic integrated circuit (MMIC) LNA with a novel CC-HEMT-based device employed in a 1 μm-gate-length technology. The results demonstrate that the LNA using CC-HEMT (composite-channel HEMT) has higher gain, lower noise and better linearity than the LNA using conventional AlGaN/GaN HEMTs in C-band.

2. Material structure and energy band profile

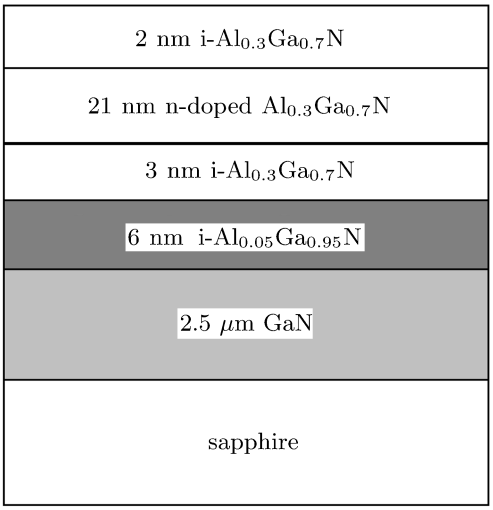


Fig.1. Schematic cross section of the $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N/GaN$ CC-HEMT device.

The $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N/GaN$ CC-HEMT structures, with the schematic cross section shown

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in Fig.1 were grown on *c*-plane sapphire substrates in an Aixtron AIX 2000 high temperature metal-organic chemical vapour deposition (HT MOCVD) system. After initial desorption, a GaN nucleation layer was grown, followed by a 2.5-nm-thick unintentionally doped GaN buffer layer. Then the layer which provided the major channel, an undoped 6 nm $Al_{0.05}Ga_{0.95}N$ layer, was grown followed by the AlGaN barrier layer with 30% Al. The barrier layers consisted of a 3-nm-thick undoped spacer, an n-doped (2×10^{18} cm^{-3}) 21-nm-thick carrier supplier layer, and a 2-nm-thick undoped cap layer. Different from the conventional AlGaN/GaN HEMT, a thin layer (6 nm) of AlGaN with 5%Al incorporated between the $Al_{0.3}Ga_{0.7}N$ barrier and the GaN buffer. This special structural energy band profile of CC-HEMT is shown in Fig.2. Due to the conduction band discontinuity, there are two hetero-interfaces. The upper one lies between the barrier and the channel layers, the lower one between the channel layer and the buffer. These two hetero-interfaces result in two 2D electron gas channels. It is supposed that most electrons are located in the upper channel (major channel), while the lower channel only accommodates a few electrons (minor channel). Meanwhile, the barrier height at the lower hetero-interface should be lower enough to ensure a strong coupling between the two channels to avoid two G_m peaks. The electrons in the minor channel can compensate the reduction of carrier density in the major channel due to the lower polarization charge density provided by an $Al_{0.3}Ga_{0.7}N$ channel layer.

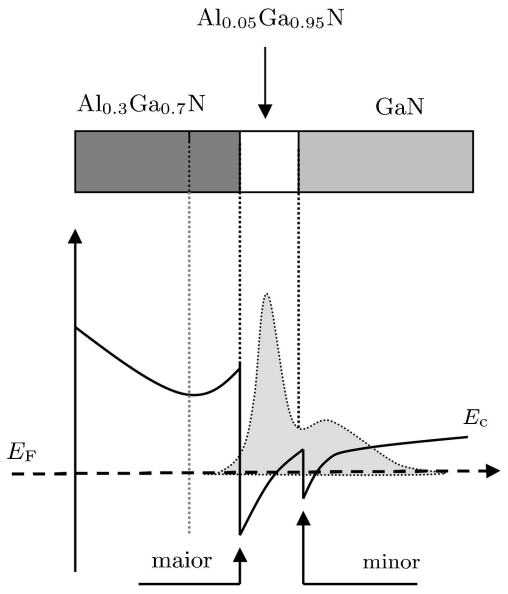


Fig.2. Schematic band profile and carrier distribution in a CC-HEMT structure.

On the other hand, minor channel shields transverse *E*-field and reduces it. So, the carrier distribution is pulled away from the barrier/channel interface in a CC-HEMT. Furthermore, at low drain current levels at which LNAs usually operate, a significant amount of carriers are located in the minor channel at the $Al_{0.05}Ga_{0.95}N$/GaN interface and are far away from the $Al_{0.3}Ga_{0.7}N$ barrier. As a result, carrier scatterings by the barrier are reduced and lower noise figure is expected, similar to what is reported for an HEMT with an inserted AlN layer in the barrier.

3. Circuit design and fabrication

MMIC LNA includes active CC-HEMT and passive components such as spiral inductors, metal-insulator-metal (MIM) capacitors and microstrip transmission lines. The fabrication steps of the integrated circuit include mesa isolation, source/drain ohmic contacts and gate contact formations, silicon nitride deposition and etching, polyimide gelatinization and developing, air-bridge and electroplating. The cross section of MMIC LNA process is shown in Fig.3. Polyimide dielectric is inserted between the metal traces and GaN buffer in order to reduce loss in transmission lines and improve the quality factor of inductors.

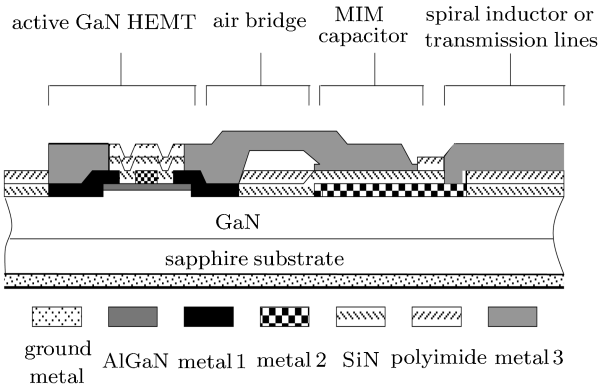


Fig.3. The cross section of MMIC LNA.

CC-HEMT in designed LNA has the gate length of 1μm and gate width of 100 μm. The measured results show that the maximum drain current density is 750 mA/mm, DC extrinsic transconductance (G_m) is 150 mS/mm, and G_m is quite flat and remains close to its peak value when drain current (I_{ds}) or voltage V_{gs} increases. The small signal *S*-parameter and noise figure of CC-HEMT are measured by using an Agilent

8722ES network analyser. Figure 4 shows measured impedances with minimum noise figure at frequency 1–15 GHz. The MMIC LNA was designed using Agilent Advanced Design System (ADS) software and the schematic circuit is shown in Fig.5. Where Z_0 is characteristic impedance and here $Z_0 = 50\Omega$. A single-stage design was employed in this design. Spiral inductors and MIM capacitors were used to form the input and output matching network of the LNA. The input matching network was designed for optimum noise figure as shown in Fig.4. At a frequency 6 GHz, the impedance is (88.4+j117.65) with minimum noise figure. So, an input matching impedance (88.4+j117.65), which is comprised of spiral inductor ($L_1 = 2.4$ nH) and MIM capacitor ($C_1 = 0.08$ pF), is designed. The output matching network which is comprised of spiral inductor ($L_2 = 3.55$ nH) and MIM capacitor ($C_2 = 0.07$ pF) is designed for optimum small signal gain according to centre frequency of 6 GHz. Figure 5 shows the schematic of the finished LNA.

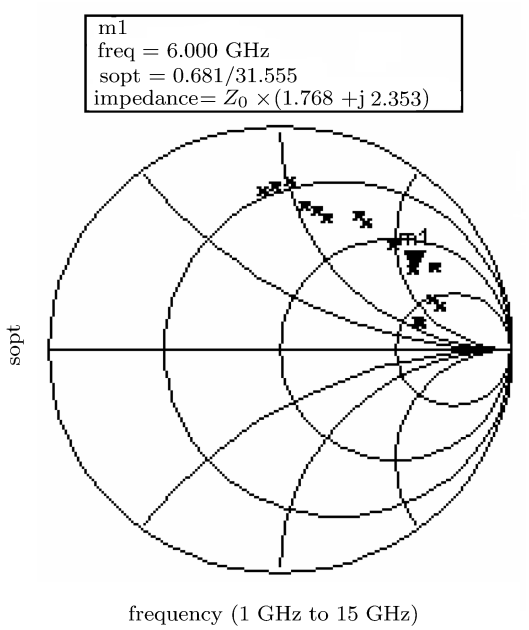


Fig.4. Measured Smith Chart with optimum noise figure at frequency of 1–15 GHz.

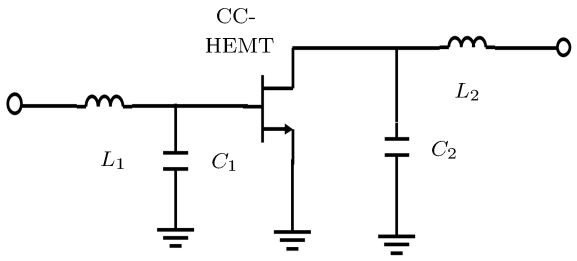


Fig.5. Schematic of MMIC LNA.

4. Circuit performances

An Agilent N8975A noise figure meter and N4002A noise figure test set were used to measure the LNA noise figure at frequency 1–10 GHz. Figure 6 shows the measured noise figure of MMIC LNA. A noise figure of 2.4 dB is obtained at 6 GHz. The low noise figure of MMIC LNA is contributed from the novel low noise CC-HEMT and high quality inductor. The gain and the return loss at the input and the output are shown in Fig.7. At 6 GHz, the LNA exhibits a gain of 12.3 dB, and the return losses are −6 dB and –16 dB at input and output, respectively. The nonlinear behaviour of LNA has also been investigated. Figure 8 shows the curves of $P_{\rm out}$, IMD3 (third-order intermodulation distortion) versus $P_{\rm in}$, which were performed by using a two-tone signal at 6 GHz with a 100 kHz offset frequency. The IIP3 of the LNA is 13 dBm in the linear region, and the LNA shows a very high-dynamic range.

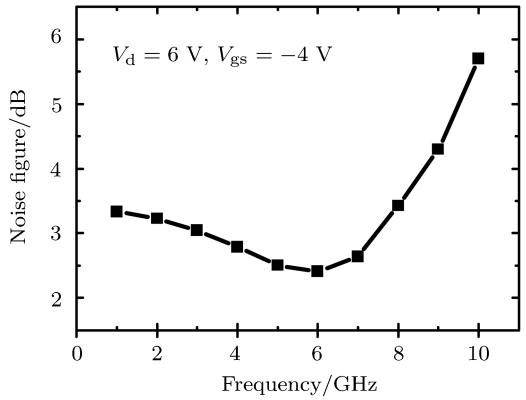


Fig.6. Noise figure versus frequency of the LNA at $V_{\rm ds} = 6$ V, $V_{\rm gs} = -4V$.

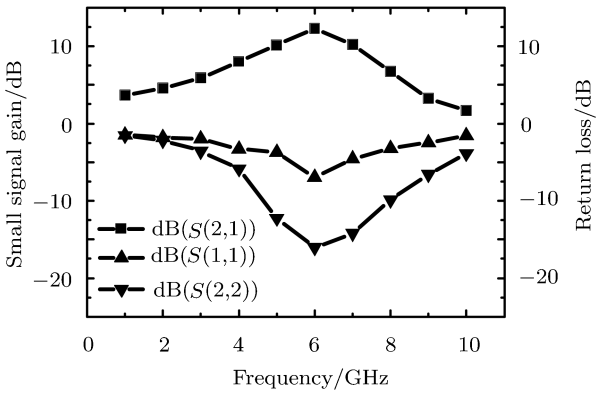


Fig.7. Small signal gain, input and output return loss of the LNA at $V_{\rm ds} = 6$ V, $V_{\rm gs} = -4V$.

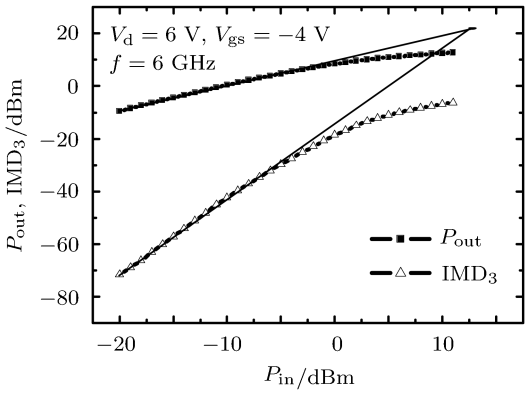


Fig.8. Linearity of the LNA at 6GHz.

5. Conclusions

A monolithic C-band low noise amplifier using $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N/GaN$ HEMT has been reported. The LNA with 1 μm × 100 μm HEMT device shows a noise figure of 2.4 dB and an associated gain of 12.3 dB at 6 GHz. An IIP3 of 13 dB is obtained. Smaller gate length is expected to result in better noise figure and higher gain. These results indicate the great potential of the $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N/GaN$ CC-HEMTs for the LNA in the next-generation wireless communication systems.

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