Fabrication of 150-nm Al$_{0.48}$In$_{0.52}$As/Ga$_{0.47}$In$_{0.53}$As mHEMTs on GaAs substrates

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Received March 3, 2012; accepted March 28, 2012; published online November 21, 2012

High performance 150-nm gate-length metamorphic Al$_{0.48}$In$_{0.52}$As/Ga$_{0.47}$In$_{0.53}$As high electron mobility transistors (mHEMTs) with very good device performance have been successfully fabricated. A T-shaped gate is fabricated by using a combined technique of optical and e-beam photolithography, which is beneficial to decreasing parasitic capacitance and parasitic resistance of the gate. The ohmic contact resistance $R_c$ is as low as 0.03 $\Omega \cdot \text{mm}$ when using a novel ohmic contact metal system (Ni/Ge/Ti/Au). The devices exhibit excellent DC and RF performance. A peak extrinsic transconductance of 775 mS/mm and a maximum drain current density of 720 mA/mm are achieved. The unity current gain cut-off frequency ($f_T$) and the maximum oscillation frequency ($f_{max}$) are 188.4 and 250 GHz, respectively.

AlInAs/GaInAs, mHEMTs, GaAs substrate, T-gate

PACS number(s): 85.30.Tv, 77.55.+f, 81.15.Ef, 81.15.Gh

Citation: Wu X F, Liu H X, Li H O, et al. Fabrication of 150-nm Al$_{0.48}$In$_{0.52}$As/Ga$_{0.47}$In$_{0.53}$As mHEMTs on GaAs substrates. Sci China-Phys Mech Astron, 2012, 55: 2389–2391, doi: 10.1007/s11433-012-4910-7

The InAlAs/InGaAs/InP high-electron mobility transistor (HEMT) is promising due to the highest gain and lowest noise figure for any three-terminal device at millimeter wave frequencies with a high current gain cut-off frequency ($f_T$) of 562 GHz [1] and the maximum oscillation frequency ($f_{max}$) of 600 GHz [2]. However, although InP-based devices have shown superior performance in higher frequency and power applications, the cost, size, and fragility of the InP wafers hinder the commercial applications of InP HEMT devices. In order to combine the advantages of GaAs and InP materials, GaAs-based mHEMTs were grown on semi-insulating GaAs substrates using a composition grading buffer technique, which will include the advantages of both InP-based HEMTs and GaAs substrates. Therefore, metamorphic high electron mobility transistors (mHEMTs) on GaAs substrates are becoming increasingly important for the fabrication of millimeter-wave MMICs with high power and low noise applications [3,4]. There are many reports on the fabrication of GaAs-based mHEMTs grown by MBE [5,6] or MOCVD [7].

In this work, the 150-nm gate-length Al$_{0.48}$In$_{0.52}$As/Ga$_{0.47}$In$_{0.53}$As mHEMT on GaAs substrates with a combined optical and e-beam photolithography technology was successfully fabricated and excellent DC and RF performance was achieved.

1 Device structure and fabrication

Metamorphic AlInAs/GaInAs HEMT (mHEMT) layers were grown by molecular beam epitaxy (MBE) on 4-in (001) oriented semi-insulating GaAs substrates. The epitaxial layer structure is shown in Table 1. A 1-µm-thick In...
graded AlInAs metamorphic buffer layer was grown on the GaAs substrate, followed by a 300-nm-thick undoped AlInAs buffer layer. To accommodate the lattice mismatch between the GaAs substrate and AlInAs/GaInAs layers, we used the low temperature, linearly graded buffer layer technique [8]. The growth was initiated at a low temperature (below 400°C) to avoid island formation and propagation of misfit dislocations. Then, the metamorphic HEMT active layer was grown at a substrate temperature of about 500°C. An 18-nm undoped Ga0.47In0.53As channel was grown on the buffer layer, followed by a 3-nm undoped Al0.48In0.52As spacer layer, a silicon planar doping of 10¹³ cm⁻², a 20-nm undoped Al0.48In0.52As Schottky contact layer and a 15-nm Ga0.47In0.53As cap layer doped at 5x10¹⁸ cm⁻³. With the cap layer removed, the results of Hall mobility measurement indicate a 2-DEG electron concentration of 3.2x10¹² cm⁻² with a mobility of 9300 cm²/V·s at room temperature and a 2-DEG density of 3.4x10¹² cm⁻² with a mobility of 24500 cm²/V·s at 77 K.

A 150-nm T-gate device was fabricated. Mesa isolation was achieved by wet chemical etching. The novel metal structure (Ni/Ge/Ti/Au) was used to obtain excellent ohmic contact. The Ni/Ge/Ti/Au metals were evaporated, followed by a rapid thermal annealing at 360°C for 50 s. Using the transmission line model (TLM), a contact resistance of about 0.03 Ω·mm was obtained due to optimization of ohmic contact metal systems and alloying conditions, which is very important for improving frequency characteristics of HEMTs. The T-gates were defined by a two-stage electron beam lithography process as shown in Figure 1. A 100-nm-thick SiNx film was deposited by PECVD to define the gate footprint, and to mechanically support the T-shaped gate. After etching of the SiNx film with CF₄/O₂ reactive ion etching (RIE), the gate-head pattern was formed by a bilayer PMMA/P(MMA-MAA) process. The gate recess etch was performed using a mixture of succinic acid and hydrogen peroxide with an AlInAs/GaInAs etch selectivity greater than 1000 [9]. Thus a very uniform drain current was measured as gate recess was etched by succinic-acid solution with etching time 15 s. Finally, Ti/Pt/Au was deposited as the Schottky gate contact.

2 Results and analysis

The 150-nm T-gate metamorphic HEMT’s were characterized on-wafer for DC and RF performance. The device exhibits excellent DC I-V characteristics with a slight increase of output conductance at high V_DS, which indicates a low short channel effect. Moreover, good pinch-off characteristics and the saturation of drain current are observed. The DC I-V characteristics of a typical AlInAs/GaInAs mHEMT with 150-nm gate-length are shown in Figure 2. The maximum drain current measured at V_GS=0.2 V and V_DS=1.5 V was 720 mA/mm. The I-V curves show a little kink effect, which shows that impact ionization happened in the InGaAs channel. Figure 3 shows the transfer characteristics. The maximum extrinsic transconductance is 775 mS/mm at V_GS=−0.5 V and V_DS = 1.2 V. The threshold voltage, V_th, is defined by a linear extrapolation of the square root of drain current versus gate voltage to zero current. V_th was measured as −0.9 V at V_DS=1.2 V. The device is a depletion-mode transistor.

The S-parameters of 100-µm-wide mHEMT’s were measured using an on-wafer Cascade Microtech probe station and an HP8722 analyzer from 0.1 to 39.5 GHz. Open on-wafer de-embedding structures were used to determine