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AlSb/InAs HEMTs with a TiW/Au gate metalization for improved stability

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Abstract

We report on the fabrication and characteristics of AlSb/InAs high electron mobility transistors (HEMTs) with a TiW/Au gate metalization. Using gate leakage and *S*-parameter measurements as a measure of stability, the HEMTs were found to be thermally stable up to 180 °C when heat treated in a H_2/N_2 ambient.

Keywords: TiW; HEMTs; HFETs; AlSb; InAs

1. Introduction

AlSb/InAs high electron mobility transistors (HEMTs) have intrinsic advantages for next generation high-speed, low-power amplifiers and logic circuits in applications that require lightweight power supplies, long battery lifetimes, improved efficiency, or high component density. They are potential candidates for these applications due to the attractive material properties of this heterojunction material system that include a high peak electron velocity at low electric field and high values of mobility and channel conductivity. As a result, intrinsic f_T values of 250 GHz have been obtained at a V_{DS} of 600 mV for a 0.1 μm gate length [1]. Also an f_T of 90 GHz has been obtained at a V_{DS} of only 100 mV [2]. Furthermore, simulations of logic circuits that combine the HEMTs with resonant tunneling diodes predict a power dissipation of only 0.3 mW/gate at 20 Gb/s when biased at 400 mV [3]. The potential payoffs associated with this material system are, however, dependent on further improvements in the technology. One goal is to improve the stability of the gate diode to make the HEMT less susceptible to degradation with bias or heat treatment. A TiW-based contact was investigated since TiW contacts on GaAs have been shown to be thermally stable up to temperatures above 650 °C [4]. A second goal is the reduction of the gate leakage current, which is a common problem in AlSb/InAs HEMTs and impacts low-noise amplifier performance by compromising the noise figure. To reduce gate leakage current caused by damage due to dry etching, the oxygen plasma surface pretreatment was optimized. In this paper, we report on the improved thermal stability and leakage current characteristics of AlSb/InAs HEMTs that were fabricated with a TiW/Au gate metalization.

2. Gate process development

Two aspects of the gate fabrication process were investigated. First, the use of a TiW/Au (175 Å/1000 Å) metalization was examined to improve the thermal stability of the gate diode. HEMTs with a Cr/Au gate metalization fabricated previously have exhibited a susceptibility to gate leakage current increases under

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bias as well as with heat treatment as low as 120 °C. X-ray photoelectron spectroscopy (XPS) measurements of the Cr/Au contact on AlSb/InAs HEMT material heat treated at 120 °C have indicated Cr diffusion into the semiconductor. An additional benefit of a more thermally stable gate contact is to enable the use of a self-aligned gate process where the source–drain contacts are deposited and heat treated after the gate metal has been deposited. Such a self-aligned technology is helpful in high-speed transistors where very low access resistance is needed to reduce the parasitic delays that can significantly mask the intrinsic speed.

Although TiW is typically sputter-deposited due to its high melting point, the TiW/Au metalization reported here was deposited by e-beam evaporation to minimize surface damage. The TiW source used in the evaporation had a composition of 90% W and 10% Ti. XPS was used to characterize the TiW layer. A composition versus depth profile of a 100 Å thick TiW layer that was evaporated on typical HEMT material is shown in Fig. 1. Sputter profiles were made using 3 kV Ar^+ ions rastered over an area of approximately 2 mm^2. Estimates of the relative atomic amounts of the recorded elements were made with a program supplied with the spectrometer. The observation of several elements at the same time in the profile is due to the attenuation lengths of the elements being approximately the same as the depth of the layers. Therefore signals will appear in the spectra even if an element is not in the top most atomic layer. The sputter rate is estimated to be ≈0.7 Å/s. The measurement indicates that the composition of the deposited layer is ≈65% W and 35% Ti, which remained fairly constant as a function of depth. The difference in the concentration of Ti and W in the layer relative to the source is believed to be due to the substantial difference in vapor pressures of these materials. The drop in the Ti and W concentrations that appears at the beginning of the measurement is due to the presence of an oxide at the surface (oxygen not shown in the figure).

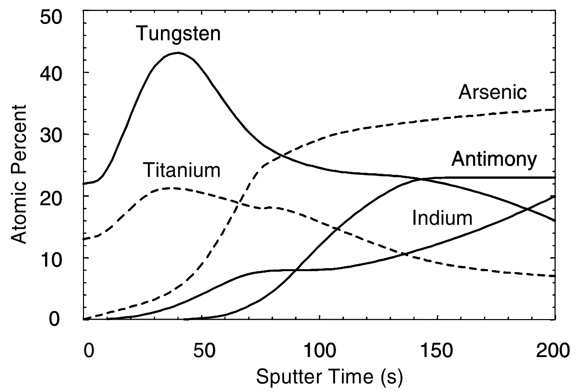

Fig. 1. XPS spectra of TiW metalization.

The second aspect of the gate fabrication process that was investigated was the effect of the oxygen plasma surface pretreatment on the gate leakage current. It should be noted that an oxygen plasma surface pretreatment is commonly required in the e-beam lithography process to remove residual PMMA. The pretreatment was optimized to minimize damage. In the fabrication of recessed-gate HEMTs using a dry etch process, damage is a well-known problem. Experiments at NRL have indicated that the Sb-based HEMT material is highly susceptible to damage due to dry etching. In previous HEMT runs, the oxygen plasma surface pretreatment was performed in a barrel etcher for 60 s at a power of 50 W. For the HEMTs reported here, the sample was etched in a parallel-plate etcher for 30 s at a power of 5 W.

3. HEMT design and fabrication

The HEMT material was grown by solid-source MBE at 510 °C on a semi-insulating (1 0 0) GaAs substrate. A 2.5 μm undoped AlSb buffer layer was used to accommodate the 7% lattice mismatch. A cross-section of the material layer design is shown in Fig. 2. The InAlAs layer enables the use of a gate recess etch into the upper barrier material prior to gate metal definition, which otherwise would be prohibited by the high reactivity of the AlSb in air. Further details related to the HEMT design have been previously reported [1]. The sheet carrier density and mobility of the starting material at 300 K were 1.9×10^{12} cm^{-2} and 20,000 cm^2/V s, respectively. The HEMTs were fabricated using Pd/Pt/Au source and drain ohmic contacts which were formed by heat treatment on a hot plate. The gate was then formed using PMMA e-beam lithography and lift-off techniques. Prior

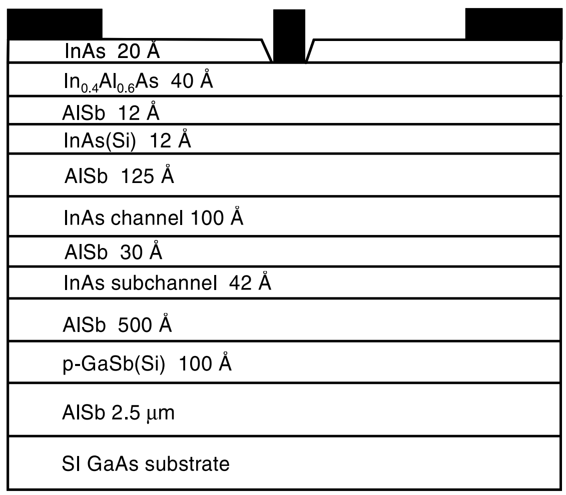

Fig. 2. HEMT starting material.

to deposition, the sample was given an O_2 plasma etch as described earlier, followed by a 10 s etch in a citric-acid-based solution to remove the InAs cap layer. Finally, device isolation was achieved by wet chemical etching. With this etch, a gate air bridge was formed which extends from the channel to the gate bonding pad.

4. HEMT characteristics

The drain characteristics obtained for a HEMT with a 0.2 μm gate length are shown in Fig. 3. The maximum transconductance at $V_{DS} = 0.5$ V and $V_{GS} = -0.45$ V is 750 mS/mm. The *S*-parameters of the HEMTs were measured on-wafer from 1 to 40 GHz. Based on the usual 6 dB/octave extrapolation, an f_T of 90 GHz and an f_{max} of 80 GHz were obtained at $V_{DS} = 0.5$ V and $V_{GS} = -0.5$ V. These values are comparable to those obtained previously for 0.2 μm gate HEMTs on this material, but the gate leakage current at low drain bias was reduced by more than an order of magnitude. The gate current characteristics are shown in Fig. 4. At $V_{DS} = 0.2$ V and $V_{GS} = -0.5$ V, a gate leakage current of 900 nA was measured. This gate leakage current at low drain bias is the lowest reported for an AlSb/InAs HEMT with this gate-channel spacing and sheet carrier density. The decrease is believed to be due to a reduction in defect-assisted tunneling through the barrier. At higher drain bias, the leakage current has additional components and therefore the difference in the leakage currents between the two cases is less.

5. Temperature effects

To examine the thermal stability of the gate, the HEMTs were progressively heat treated from 90 °C to 210 °C in increments of 30 °C. Each heat treatment duration was 1 h and was performed using a hot plate in a glove box containing a H_2:N_2 (5%:95%) ambient. Only small changes in the reverse current or the *S*-parameters of the HEMT were observed prior to the 210 °C treatment. HEMTs fabricated with a Cr/Au gate on similar material and heat treated in the same manner had an increase in the reverse leakage current of more than an order of magnitude at a temperature of only 150 °C. The TiW/Au gate HEMTs also were observed to be less susceptible to degradation with bias. The improved thermal stability of the TiW/Au gate may make possible a self-aligned gate process since the ohmic contacts in these HEMTs are heat treated at only 175 °C.

The HEMT gate diode leakage current measured before and after a 1 h heat treatment at 175 °C for two representative devices is shown in Fig. 5. Diode A shows only a small increase in leakage current after heat treatment and diode B shows essentially no change.

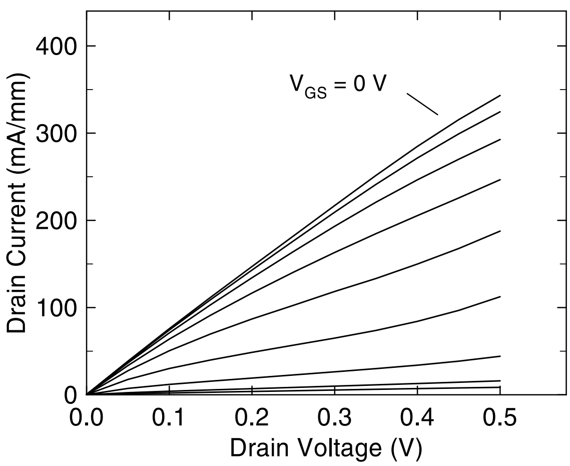

Fig. 3. HEMT drain characteristics. $L_G = 0.2$ μm, $L_{DS} = 2.0$ μm, $W_G = 50$ μm, $V_{GS} = 0.1$ V/step.

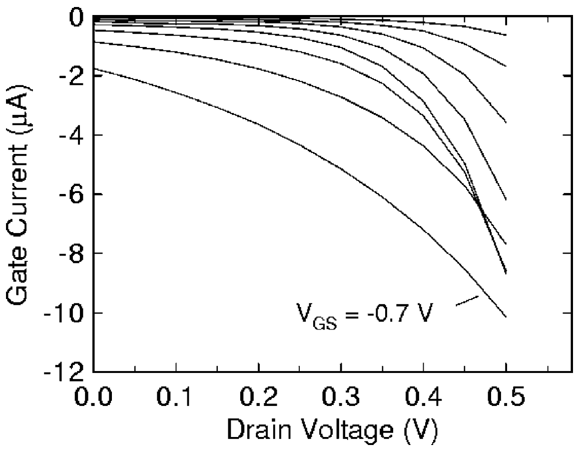

Fig. 4. HEMT gate current versus V_{DS}. $V_{GS} = 0$ V to -0.7 V, $V_{GS} = -0.1$ V/step.

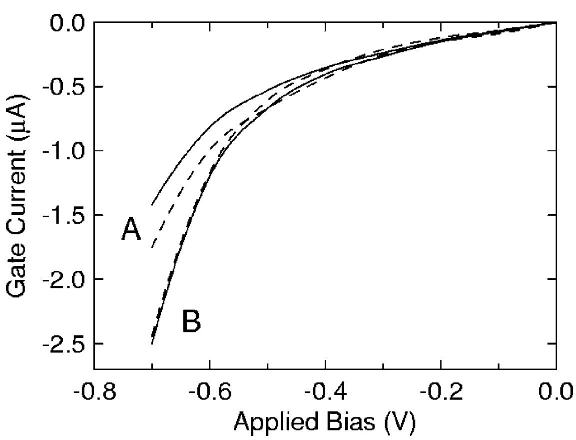

Fig. 5. HEMT gate diode current versus V_{GS} for two representative devices before (solid) and after heat treatment (dashed) at 175 °C for 1 h. $V_{DS} = 0$ V.

The thermal stability of TiW/Au diodes was also investigated. The material design was chosen to closely resemble the HEMT design shown in Fig. 1. For these structures, a non-alloyed ohmic contact was formed on the samples prior to the TiW/Au evaporation. The sample did not receive a plasma or chemical etch pretreatment prior to the evaporation. The diodes were heat treated from 90 to 300 °C in increments of 30 °C as previously described. Minimal increase in the diode current was observed prior to the 300 °C treatment. In contrast to this, when a Cr/Au metalization was deposited and heat treated in the same manner, an increase as high as an order of magnitude was observed in the diode current at a temperature of 180 °C.

These measurements indicate that the combination of the TiW/Au gate metalization and the weaker oxygen plasma pretreatment improves stability and decreases the gate leakage current. However, more experiments are required to understand the dependence of the leakage current on the material growth, HEMT design, and processing parameters.

Acknowledgements

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