Ohmic Contact Study for Gallium Nitride-Based High Electron Mobility Transistors and Ultra-Short N-Type THz Devices

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Abstract:

Gallium nitride (GaN) based high electron mobility transistors (HEMTs) and terahertz (THz) emission devices are promising technologies for high-speed, high-power applications [1]. The formation of reliable, low resistance, thermally stable ohmic contacts is a crucial part of improving device performance. In this study, we examined various metal layers for making contacts on both HEMT and THz type substrates with the goal of achieving lower transfer resistance and improved repeatability. We also tested the response of the contacts to rapid thermal annealing (RTA) to determine the optimal anneal conditions for each metal stack. Those using vanadium (V) in the first-deposited layer were the top performers for the HEMT material system, while niobium (Nb) in the first layer produced the best results for the THz material system.

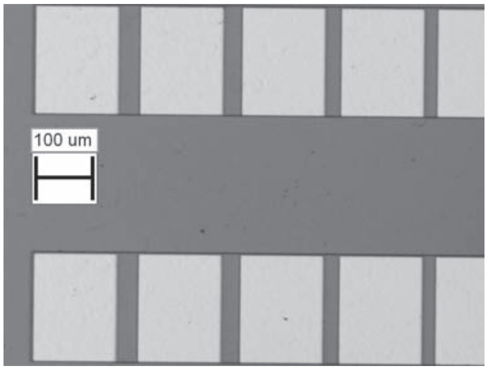

Figure 1: Overhead view of TLM structures.

Methods:

Ohmic contacts were studied for two different GaN material systems, corresponding to the two devices of interest. The HEMT material was an epitaxially-grown AlGaN/GaN heterojunction on a silicon (Si) substrate, available commercially from Nitronex. The THz material was germanium-doped n+ type GaN ($N_D \approx 2 \times 10^{20}$ cm^{-3}), grown via molecular beam epitaxy at Cornell, prior to this experiment. Each wafer was patterned with 200 μm wide, 100 nm tall rectangular mesas using a reactive ion etcher with $Ar/Cl_2/BCl_3$ chemistry. Transfer length method (TLM) patterns were created with a contact spacing that varied linearly from 5 μm to 40 μm in increments of 5 μm. The HEMT and THz material wafers were cleaved into smaller samples (~ 5 mm × 5 mm) to analyze multiple metal configurations and anneal conditions.

All of the metals in this study were deposited using e-beam evaporation, except for gold (Au) and aluminum (Al), which were evaporated thermally. Immediately prior to being loaded into the evaporator, the samples were cleaned in an oxygen plasma for 60 seconds at 100 W power to remove any residual resist in the contact areas and then immersed for 30 seconds in a buffered oxide etch solution (BOE 30:1) to remove any native oxide. All of the metal layers for a given stack were deposited *in situ*. After evaporation, a standard liftoff was performed followed by a deionized water rinse. Figure 1 shows an overhead view of two of the finished mesas and metal arrays used in this study.

Using four-point-probe technique, we measured the resistance of each TLM gap; from the linear relationship between resistance and gap length, we were able to calculate the contact resistivity ρc (in ohm-mm), the sheet resistance R_{sh} (in ohms/sq), the transfer length L_t (in μm), and the specific contact resistance R_{sc} (in ohm-cm^2) [2]. For each sample, these values were averaged over the results from many mesas with a typical 85% uniformity.

To study the thermal dependence of ohmic contact formation, we used an AG HeatPulse rapid thermal annealer (RTA) to examine a range of temperatures and times. All of the anneals were performed in a nitrogen (N_2) ambient and the carrier wafer temperature was measured via thermocouple.

Terahertz Material Results:

A complete thermal profile of every metal configuration investigated was neither feasible nor necessary for our purposes, which were to find the lowest contact resistance. Table 1 summarizes the best contact resistances we were able to achieve from each metal stack and the associated anneal conditions.

Note that where marked with an asterisk, the anneal conditions shown were only the final temperatures used after previous, lower-temperature anneals on the same sample. In general,

Metal Stack	Layer Thicknesses (Å)	Rc (ohm-mm)	Rsh (ohms/sq)	Lt (µm)	Rsc (ohm-cm²)	Anneal Conditions
Sc	1100	0.943	25.7	39.3	1.50E-05	as deposited
Sc/Au	500 / 600	0.788	32.1	25.1	7.99E-06	30 sec at 350 °C
Ti/Sc/Mo/Au	100 / 600 / 400 / 450	0.750	36.6	20.6	6.25E-06	30 sec at 650 °C *
V/Al/V/Au	150 / 800 / 200 / 1000	0.141	39.5	3.63	2.09E-07	30 sec at 650 °C *
Nb/Al/Nb/Au	150 / 800 / 200 / 890	0.136	42.4	3.22	1.76E-07	30 sec at 700 °C *
Nb/Au	150 / 300	0.223	37.2	6.00	5.35E-07	30 sec at 600 °C *

Table 1: Optimal contact resistances for Terahertz material.

Metal Stack	Layer Thicknesses (Å)	ρc (ohm-mm)	Rsh (ohms/sq)	Lt (µm)	Rsc (ohm-cm²)	Anneal Conditions
Sc	1100	(not ohmic)	n/a	n/a	n/a	n/a
Sc/Au	500 / 600	(not ohmic)	n/a	n/a	n/a	n/a
Ti/Sc/Mo/Au	100 / 600 / 400 / 450	(not ohmic)	n/a	n/a	n/a	n/a
Ti/Al/Mo/Au	150 / 900 / 400 / 500	(not ohmic)	n/a	n/a	n/a	n/a
Ti/Al/Si/Au	125 / 700 / 350 / 1000	0.427	1170	0.362	7.17E-08	30 sec at 750 °C *
Ti/Al/Si/Cu	125 / 700 / 350 / 1000	1.24	1700	0.728	3.60E-07	30 sec at 800 °C *
Ta/Ti/Al/Mo/Au	75 / 150 / 900 / 400 / 500	2.01	899	2.28	1.87E-06	60 sec at 700 °C then 20 sec at 800 ° C
V/Ti/Al/Mo/Au	75 / 150 / 900 / 400 / 500	0.796	591	1.37	4.52E-07	60 sec at 700 °C then 20 sec at 800 ° C
V/Al/V/Au	150 / 800 / 200 / 1000	0.521	763	0.677	1.74E-07	40 sec at 775 °C
V/Al/Si/Au	150 / 800 / 350 / 1000	0.984	1230	0.788	3.31E-07	30 sec at 800 °C *
V/Al/Si/Cu	150 / 800 / 350 / 1000	0.176	1000	0.176	1.24E-06	30 sec at 800 °C *
V/Al/V/Cu	150 / 800 / 200 / 1000	(not ohmic)	n/a	n/a	n/a	n/a
Nb/Al/Nb/Au	150 / 800 / 200 / 890	0.851	926	1.02	5.53E-07	30 sec at 850 °C *
Nb/Au	150 / 300	(not ohmic)	n/a	n/a	n/a	n/a

Table 2: Optimal contact resistances for HEMT material.

the anneals were performed in steps of 50°C beginning at 350°C, annealing for 30s at each temperature, and letting the sample return to room temperature for measurement between successive anneals

HEMT Material Results:

The nature of the AlGaN barrier layer made forming good contacts to the undoped HEMT material more challenging. In contrast to the THz material, none of the as-deposited metal stacks exhibited a linear current/voltage relationship. Annealing, often beyond 500°C, was required before the contacts became ohmic. Several of the metal stacks exhibited nonlinear current/voltage relationships regardless of anneal condition. Table 2 summarizes the best results achieved for contacts to the HEMT material.

Summary:

The metal stack Nb/Al/Nb/Au exhibited the lowest contact resistance to the THz material, with good edge acuity and thermal stability. For the HEMT material system, V-based stacks demonstrated the best overall performance, but several exhibited high sheet resistances after annealing. The TLM model assumes uniform sheet resistance throughout the semiconductor, including under the contacts, and is not valid when this assumption is violated [2].

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