APPLICATION NOTE

Exploring off-state breakdown of GaAs pHEMTs at cryogenic temperatures

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ABSTRACT

A study of off-state breakdown in a commercial pseudomorphic high electron-mobility transistor (pHEMT) has been performed in a cryogenic probe station with automated temperature control. Thermionic field effect transport across the Schottky barrier was identified as the dominant off-state breakdown mechanism by temperature-dependent transport measurements.

I. INTRODUCTION

Temperature-dependent transport measurements of developing semiconductor devices at cryogenic temperatures are an essential tool for exploring the complex conduction mechanisms that can arise from material defects, surface impurities, and novel architectures. By eliminating the need to package and wire a device prior to testing, on-wafer probing can expedite cryogenic device testing; however, variable temperature device probing measurements typically require continuous user intervention in order to land probes on the device under test, perform transport measurements, then lift the probes prior to setting a new temperature. Flexible probe tips have eliminated the need to lift and land probes for many variable temperature measurements. As a result, fully automated, variable temperature device testing can be realized in a cryogenic probe station. In this work, characterization of the off-state breakdown in a commercially available n-type GaAs pseudomorphic high electron-mobility transistor (pHEMT) is demonstrated in an automated variable cryogenic-temperature probe station.

II. EXPERIMENTAL SETUP

The 180 µm square pHEMT device die was mounted to sapphire substrate with an ultra-thin layer of two component epoxy resin. The sapphire substrate was mechanically clamped to a grounded sample holder mounted on the cold stage of a Lake Shore CRX-4K cryogen-free probe station and cooled to base temperature. 25 µm diameter tungsten continuously variable temperature (CVT) tips were landed on the 70 µm wide, gold-coated contact pads at 4.7 K and remain in contact with the device throughout the temperature cycles up to 310 K[1].

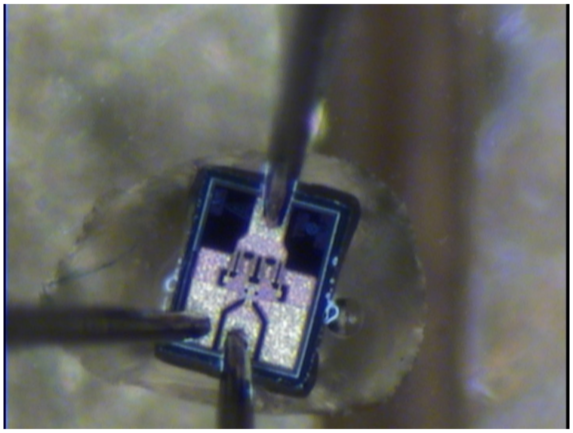

Figure 1. pHEMT device mounted on the sample stage of the cryogenic probe station.

Transport properties at each temperature are measured with a Keithley 4200 semiconductor parameter analyzer using a medium gain SMU. The Lake Shore Model 336 controlling the probe station sample stage temperature is programmatically operated by an instrument library integrated into the Keithley 4200 measurement platform[2]. The software driver cycles through a series of setpoint temperatures in the measurement profile. For each planned device temperature, the temperature controller ramps the setpoint to the target temperature and the instrument driver monitors the stage temperature for adequate stability; a 10 minute, post-stabilization wait period occurs prior to initiating electrical testing in order to fully thermalize the substrate and device to the sample stage.

III. RESULTS

The measured DC output characteristics for the pHEMT device at 310 K are shown in Figure 2. A sharp kink or up-turn in the channel conductance is observed in the near pinch-off (gate bias = -1.0 V) I-V curve and is attributed to a gate-drain breakdown. As gate-drain breakdown limits the maximum power handling capability of the device, this effect has been a topic of interest since the inception of pHEMT device architectures.

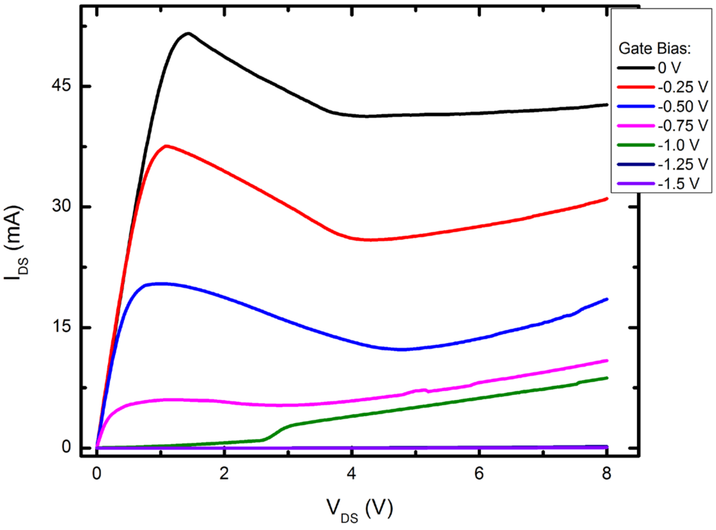

Figure 2. Output characteristics of this pHEMT device at 310 K.

Off-state breakdown in pHEMT devices result from the complex interplay of material properties and device geometry. Proposed mechanisms for the breakdown have distinct temperature dependencies which can be used to discern the dominant mechanism in a given device architecture. These mechanisms were explored in the transfer characteristics of the commercial pHEMT used in this work.

The transfer characteristic of the pHEMT device (Figure 3) as a function of temperature shows a gradual decrease in the pinch-off voltage from -1.5 V to -1.1 V as the device is cooled from 310 K to 10 K, and a non-negligible off-state current is observed at temperatures above 210 K and increases at higher temperatures.

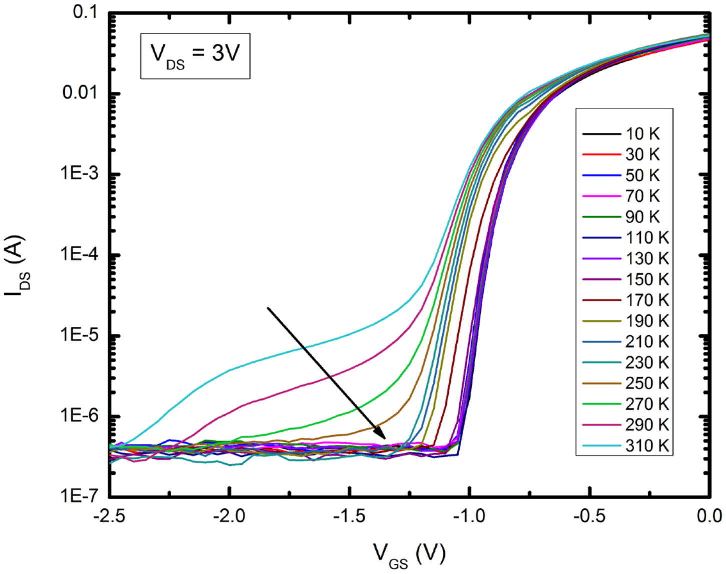

Figure 3. Transfer curves of the pHEMT device as a function of temperature.

Typically, excess off-state channel current results from carrier transport across the Schottky barrier at the gate contact and/or carrier generation in the channel through impact ionization[3]. For the latter effect, large electric fields in the channel accelerate carriers to sufficiently high energy such that it can create an electron-hole pair by colliding with an electron in the valence band. The impact ionization rate increases with increasing electric field between gate and drain but *decreases* with increased temperature. As the observed off-state current has the opposite temperature dependence, impact ionization is not the dominate effect driving room temperature off-state breakdown in this device.

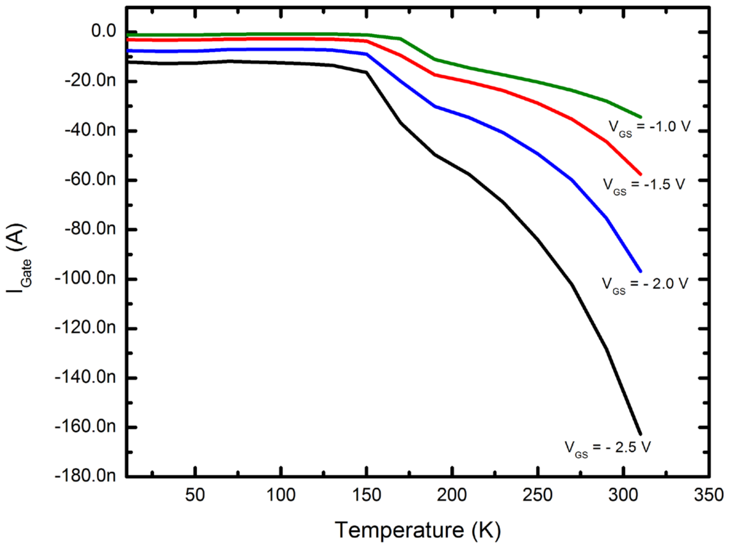

Figure 4. Temperature-dependent pHEMT gate current during measurement of transfer curves (V_{DS} = 3 V).

On the other hand, off-state breakdown due to transport across the Schottky barrier typically manifests as a rapid increase in the gate current with temperature as well as gate-drain voltage (Figure 4). Transport across the barrier is described by a thermionic field emission (TFE) model which includes both tunneling (I_T) and thermionic emission (I_{TE}) mechanisms:

$$I_{TFE} = I_T + I_{TE}$$

$$I_{TFE} = \left\{K' \cdot T\int_0^{\phi_B} f_s(V) \cdot P(E) \cdot (1 - f_M)\, dE\right\} + \left\{A \cdot T^2 \exp\left(-\frac{q\phi_B}{k_B T}\right) \exp\left(\frac{qV}{k_B T}\right)\right\}$$

where $P(E)$ is the tunneling probability, f_s and f_M are the temperature-dependent Fermi distributions for the semiconductor and metal. ϕ_B is the Schottky barrier height and V is the gate-drain potential difference. K' and A are material coefficients.

Three distinct gate leakage regimes are identified in the temperature-dependent gate current for fixed source-gate voltages in Figure 4. Above 210 K, the non-monotonic temperature dependence of the gate current is indicative of a thermionic field emission mechanism. Below 150 K, the gate current is independent of temperature with a source-gate voltage dependence which suggests the barrier conduction is dominated by tunneling transport. Between 150 K and 210 K, the observed temperature dependence of the gate current indicates an intermediate breakdown mechanism—perhaps defect-assisted tunneling[4]. Switching noise in the 190 K source-drain I-V curve (Figure 5) at the breakdown threshold suggests the role of defects in the intermediate temperature leakage.

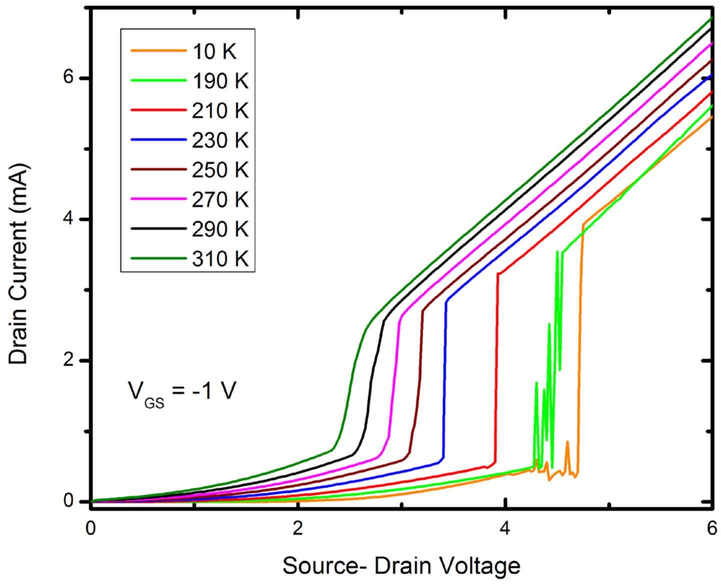

Figure 5. The evolution of off-state breakdown with temperature as seen in the Source-drain I-V curves near pinch-off.

IV. SUMMARY

In this paper, the DC electrical characteristics of a commercial pHEMT device were evaluated from 10 K to 310 K in a cryogenic probe station with automated temperature control and flexible probe tips which compensate for thermal expansion of the probe arms. Temperature-dependent characterization indicated thermionic field emission as the dominant mechanism underlying off-state breakdown in this device under ambient operating conditions.

REFERENCES

[1] Temperature range for reliable device contact with CVT tips depends on probe material, probe station model, and quality of device contact. Results will vary.

[2] Available on request from Keithley, USA.

[3] T. Baksht, S. Solodky, M. Leibovitch, G. Bunin, and Y. Shapira, “Impact ionization measurements and modeling for power PHEMT,” IEEE Transactions on Electron Devices, vol. 50, pp. 479-485, 2003.

[4] R. Menozzi, “Off-State Breakdown of GaAs PHEMTs: Review and New Data,” IEEE Transactions on Device and Materials Reliability, vol. 4, pp. 54-62, 2004.

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