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# Experimental Investigation on the Bias and Temperature Dependence of the Forward Transmission Coefficient for HEMT Technologies

Mohammad Abdul Alim, Christophe Gaquière, and Giovanni Crupi

**Abstract**—The goal of this research is to look at the effects of temperature on the forward transmission coefficient ( $S_{21}$ ) of high electron-mobility transistors (HEMTs), employing various technologies. The analysis is carried out on six different devices under different bias conditions with the ambient temperature varied from  $-40^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . The low-frequency magnitude of  $S_{21}$  is significantly reduced in GaN-based HEMTs when the temperature is increased. On the other hand, an operating bias point where this magnitude is temperature insensitive has been identified in GaAs-based HEMTs.

**Keywords**—Ambient temperature, Bias condition, Forward transmission coefficient, HEMT, Scattering-parameter measurements.

## I. INTRODUCTION

In the last decades, large efforts have been made to explore how the temperature impacts on the bias-dependent small-signal behavior of high electron-mobility transistors (HEMTs), going from low- to high-temperatures [1]–[11], in order to support the circuit design for microwave applications. Aiming at gaining insights on this research subject, this work is focused on a measurement-based analysis of the forward transmission coefficient ( $S_{21}$ ), since this is a key parameter for assessment of the device performance. The analysis was carried out using scattering (S-) parameters measurements performed in the frequency range of 45 MHz to 50 GHz with an ambient temperature ( $T_a$ ) changed from  $-40^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . The drain-source voltage ( $V_{ds}$ ) was fixed in the saturation region, whereas gate-source voltage ( $V_{gs}$ ) was changed to check its impact on the temperature-dependent behavior of  $S_{21}$ . To analyze various technologies, six different HEMT devices were considered.

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This work is structured as follows: Section II briefly describes the six analyzed HEMTs, Section III reports the experimental findings and discussion, and the last section concludes this work.

## II. STUDIED DEVICES

The studied transistors consist of six on-wafer multi-finger HEMTs fabricated using different types of technologies: gallium arsenide (GaAs) and gallium nitride (GaN) materials, lattice-matched HEMTs and pseudomorphic HEMTs (pHEMTs), single- (S-H) and double-heterojunction (D-H) HEMTs, and both virgin and multi-layer (ML) devices. The photos of the studied transistors are shown in Fig. 1. The details of the devices are:  $0.5 \times (2 \times 100) \mu\text{m}^2$  S-H GaAs HEMT (see Fig. 1(a)),  $0.5 \times (2 \times 75) \mu\text{m}^2$  S-H GaAs HEMT (see Fig. 1(b)),  $0.5 \times (2 \times 100) \mu\text{m}^2$  D-H virgin GaAs pHEMT (see Fig. 1(c)),  $0.5 \times (2 \times 100) \mu\text{m}^2$  D-H ML GaAs pHEMT (see Fig. 1(d)),  $0.25 \times (2 \times 100) \mu\text{m}^2$  GaN HEMT (see Fig. 1(e)), and  $0.15 \times (4 \times 50) \mu\text{m}^2$  GaN HEMT (see Fig. 1(f)).

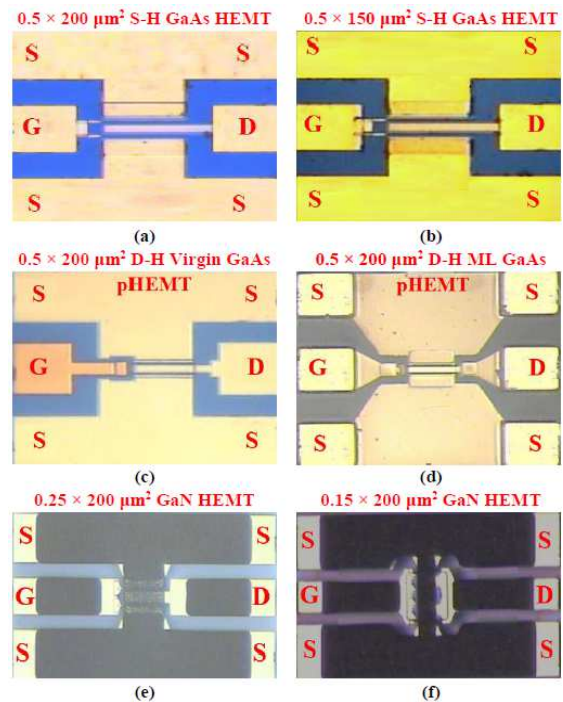


Fig. 1. Illustration of the six studied HEMTs.

The studied devices have been characterized by using a thermal probe station coupled to an HP4142B DC source and an HP8510C vector network analyzer (VNA).

### III. EXPERIMENTS AND DISCUSSION

Figs. 2-4 report the frequency dependence of the magnitude of  $S_{21}$  for the six tested devices at three different temperature conditions:  $-40^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $150^\circ\text{C}$ . The analysis is performed over the full studied frequency range (i.e., 45 MHz – 50 GHz) and at an operating bias point in the saturation region. A higher temperature leads to a significant reduction of the magnitude of  $S_{21}$ . Although this reduction can be observed practically at all frequencies, it is pronounced especially at low frequencies. This is due to the strict link between  $S_{21}$  and the transconductance, which is stronger at lower frequencies. As a matter of fact, at relatively low frequencies  $S_{21}$  can be defined as follows [12]:

$$S_{21} = -g_{m\text{Extr}}(R_0 \parallel R_{ds\text{Extr}}), \quad (1)$$

where  $R_0$  is  $50 \Omega$ ,  $g_{m\text{Extr}}$  is the RF transconductance, and  $R_{ds\text{Extr}}$  is the RF drain-source resistance.

It is worthy to mention that the magnitude of  $S_{21}$  is reduced at higher frequencies, since the reactive element contributions play a more dominant role when the frequency is increased, thereby making the link between  $S_{21}$  and the transconductance less tight.

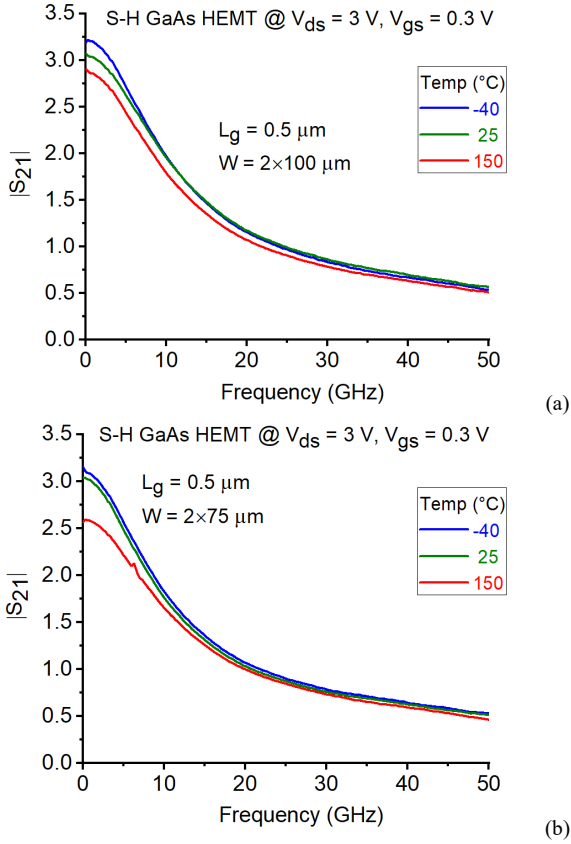


Fig. 2. Magnitude of  $S_{21}$  versus frequency under three different temperature conditions for two S-H GaAs HEMTs at  $V_{ds} = 3 \text{ V}$  and  $V_{gs} = 0.3 \text{ V}$ : (a)  $0.5 \times (2 \times 100) \mu\text{m}^2$ , (b)  $0.5 \times (2 \times 75) \mu\text{m}^2$ .

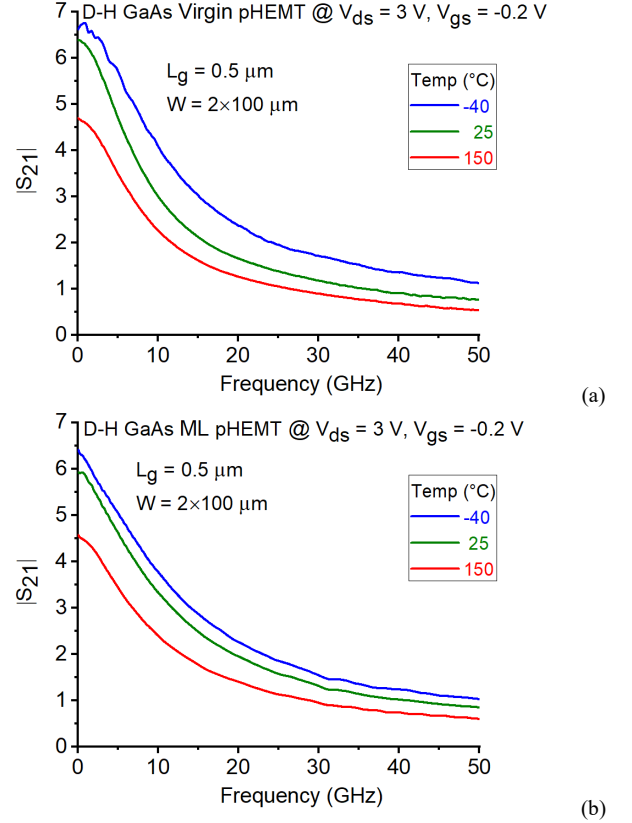


Fig. 3. Magnitude of  $S_{21}$  versus frequency under three different temperature conditions for two D-H GaAs pHEMTs at  $V_{ds} = 3 \text{ V}$  and  $V_{gs} = -0.2 \text{ V}$ : (a) Virgin:  $0.5 \times (2 \times 100) \mu\text{m}^2$ , (b) multi-layer:  $0.5 \times (2 \times 100) \mu\text{m}^2$ .

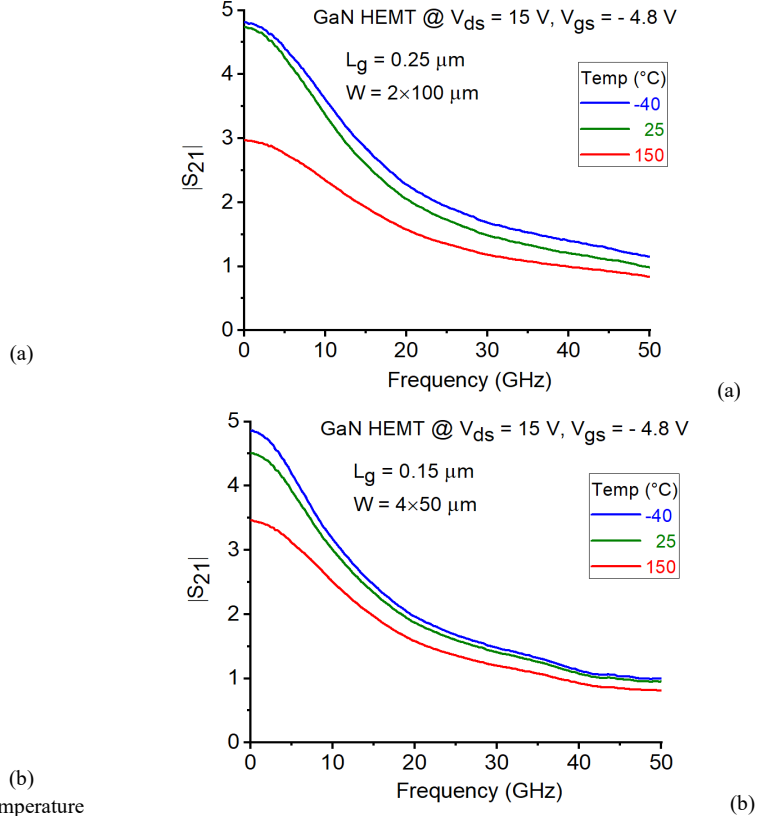


Fig. 4. Magnitude of  $S_{21}$  versus frequency under three different temperature conditions for two GaN HEMTs at  $V_{ds} = 15 \text{ V}$  and  $V_{gs} = -4.8 \text{ V}$ : (a)  $0.25 \times (2 \times 100) \mu\text{m}^2$ , (b)  $0.15 \times (4 \times 50) \mu\text{m}^2$ .

In order to focus the analysis on the behaviour  $S_{21}$  at low frequency, we investigate the data at 45 MHz, which is the lowest available frequency. Figs. 5-7 report the magnitude of  $S_{21}$  at 45 MHz versus the gate-source voltage for the six investigated devices at three different temperature conditions:  $-40^{\circ}\text{C}$ ,  $25^{\circ}\text{C}$ , and  $150^{\circ}\text{C}$ .

As can be clearly observed from the data in Figs. 5-7, the four studied GaAs-based HEMTs exhibit an operating bias point at which the low-frequency magnitude of  $S_{21}$  is temperature insensitive, which can be linked to the so called transconductance zero temperature coefficient point [8], whereas the two studied GaN-based HEMTs show a degradation in the magnitude of  $S_{21}$  at low frequency for all the considered values of  $V_{gs}$ .

The result for the GaAs-based HEMTs can be explained by the fact that the resultant impact of the temperature on the device behaviour can be ascribed to two effects acting in opposite directions when the temperature is increased: the degradation of the carrier transport properties, which plays a more dominant role by increasing  $V_{gs}$ , and the threshold voltage ( $V_{TH}$ ) shift towards more negative values, which has a more dominant role by lowering  $V_{gs}$ . In case of the GaN-based HEMTs, the worsening in the transport properties of the carriers is the predominant temperature-dependent effect for all the studied values of  $V_{gs}$ . However, it should be highlighted that for both GaAs and GaN devices, the highest value of the low-frequency magnitude of  $S_{21}$  is reduced by increasing the temperature, as the higher values are located far from the pinch-off condition.

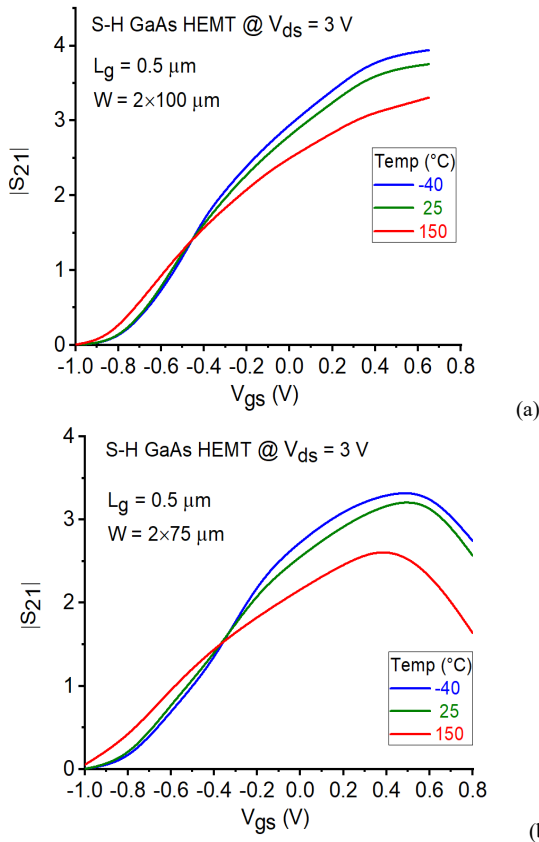


Fig. 5. Magnitude of  $S_{21}$  at 45 MHz versus  $V_{GS}$  under three different temperature conditions for two S-H GaAs HEMTs at  $V_{ds} = 3$  V: (a)  $0.5 \times (2 \times 100) \mu\text{m}^2$ , (b)  $0.5 \times (2 \times 75) \mu\text{m}^2$ .

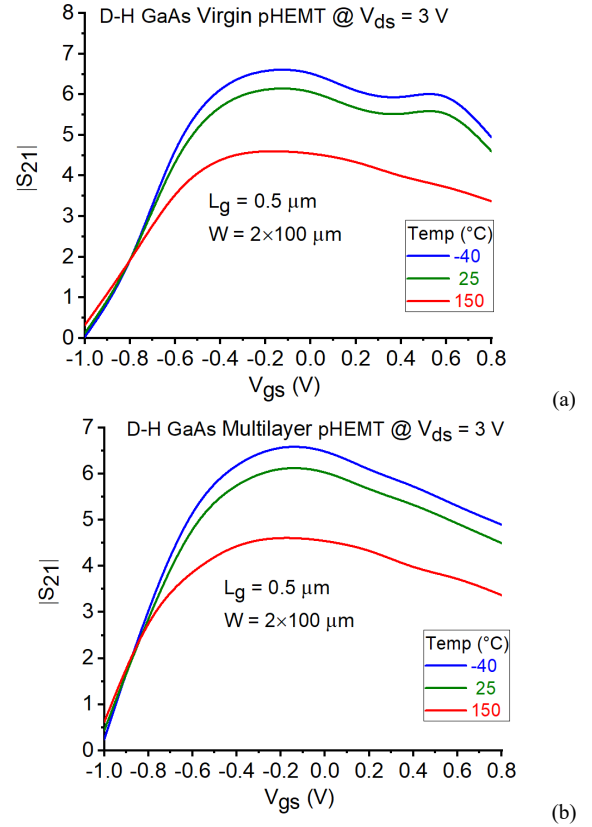


Fig. 6. Magnitude of  $S_{21}$  at 45 MHz versus  $V_{GS}$  under three different temperature conditions for two D-H GaAs pHEMTs at  $V_{ds} = 3$  V: (a) Virgin:  $0.5 \times (2 \times 100) \mu\text{m}^2$ , (b) multi-layer:  $0.5 \times (2 \times 100) \mu\text{m}^2$ .

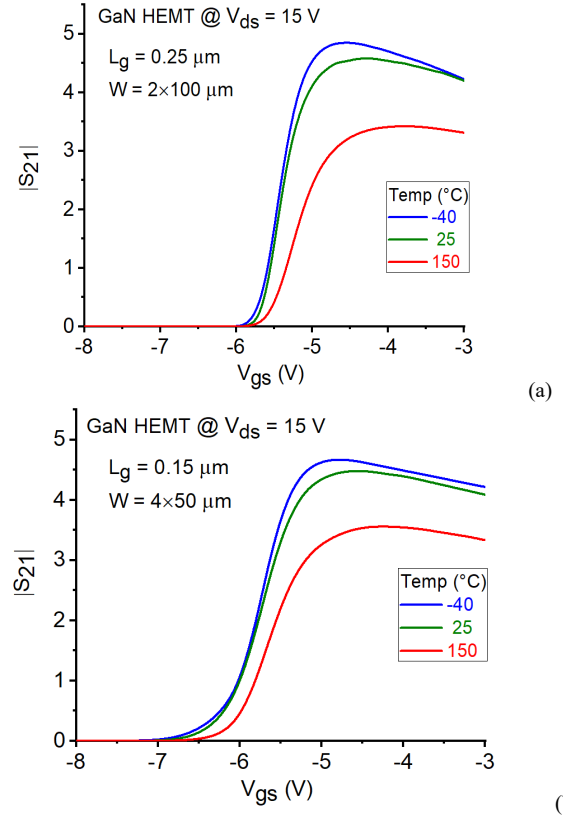


Fig. 7. Magnitude of  $S_{21}$  at 45 MHz versus  $V_{GS}$  under three different temperature conditions for two GaN HEMTs at  $V_{ds} = 15$  V: (a)  $0.25 \times (2 \times 100) \mu\text{m}^2$ , (b)  $0.15 \times (4 \times 50) \mu\text{m}^2$ .

#### IV. CONCLUSIONS

A measurement-based study has been developed to examine the temperature effects on the HEMT behaviour. This study has considered various HEMT technologies, including GaAs and GaN materials, lattice-matched and pseudomorphic HEMTs, single- and double-heterojunction HEMTs, and both virgin and multi-layer devices. The analysis has been focused on the forward transmission coefficient, which is a key figure of merit. Particular attention has been given to the low-frequency magnitude of  $S_{21}$  as this quantity can be tightly correlated to the transconductance. The reported experiments have shown that the temperature effects can strongly vary depending on the technology and bias condition.

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