

# GaAs Resistor Model Predicting Harmonic, Transient and Breakdown

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**Abstract**—A comprehensive nonlinear model of GaAs resistor is developed based on DC, pulse and power measurements. The model accounts for electrical and thermal features such as velocity saturation, self-heating and breakdown effects. The resistor nonlinearity is mainly due to the velocity saturation, and enhanced by self-heating effect. The model provides accurate performances in DC, transient and harmonic balance simulations, and is a useful tool for monolithic microwave integrated circuits (MMICs) development.

**Keywords**—MMICs; resistors; semiconductor device modeling; simulation; switches

## I. INTRODUCTION

GaAs resistor is a common component in GaAs monolithic microwave integrated circuits (MMICs), which is extensively used, for example, in switch, amplifier, and also in electrostatic discharge (ESD) protection circuit. GaAs resistor is not nearly a linear resistor as expected; it exhibits dispersion and generates harmonics. It has been found that the harmonics from resistors can be comparable to those from active devices in the switch circuit. An accurate GaAs resistor model predicting the harmonic and transient behavior is required for GaAs MMICs development.

Nonlinear resistor model has been reported in [1-2]. While the model accurately predicts the DC current-voltage (IV) behavior, it, however, overestimates the harmonics generated. Besides, the resistor model describing the transient and breakdown behaviors has not been reported yet. In this paper, a new resistor model with accurate prediction on DC, transient, harmonic, and breakdown, is proposed. The existing model is briefly reviewed in Section II, the new model development is described in Section III, and the paper is then concluded in Section IV.

## II. EXISTING MODEL

The resistors with ground-signal-ground test pad were fabricated on an experimental GaAs wafer. The sheet resistance is 340 Ohm/sq. Three resistors, named resistor A, B, and C, respectively, are characterized in terms of DC, pulse, and power measurements via the probe station. The three resistors have the same width, and their resistances are designed as 6, 12 and 24 kOhm, respectively, by adjusting the resistor length.

The measured DC IV is shown in Fig. 1. The resistor current saturates, and thus the resistance increases with increasing voltage. As proposed in [1], the DC IV performance can be fitted with (1), where  $I_S$  and  $R_0$  are the saturation current and linear resistance, respectively.

$$I = I_S \tanh\left(\frac{V}{R_0 I_S}\right). \quad (1)$$

The model is then validated with power performance. Single tone power measurement was performed at the fundamental

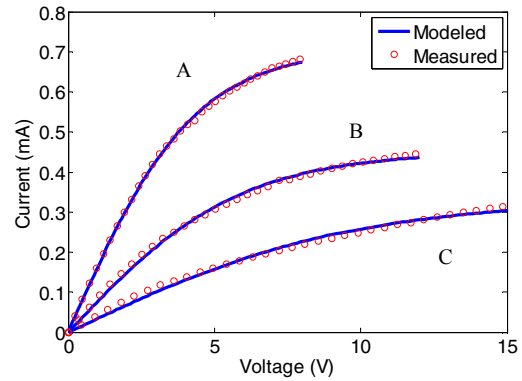


Figure 1. DC IV performance of GaAs resistor A, B and C

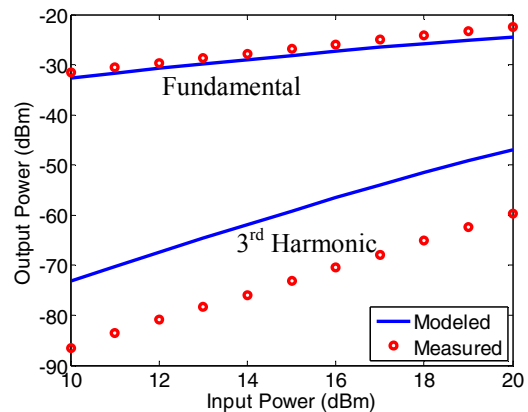


Figure 2. Single tone power performance of resistor B, measurement versus simulation with existing model

frequency of 850 MHz. Fig. 2 shows the comparison between measured and simulated the power behaviors. While agreement has been achieved for the fundamental, the simulated 3<sup>rd</sup> harmonic is much higher than the measured one. The model overestimates the harmonic generated by the resistor.

### III. NEW MODEL

#### A. Pulse Performance

The measured transient response of resistor A is shown in Fig. 3, the pulse width and period are 4 and 10 milliseconds, respectively, and the pulse height is 5V. As shown in Fig. 3, the current decreases with the time, and the time constant is in the order of millisecond. The transient behavior can be explained with self-heating effect. The decrease in current is due to the temperature increase inside the resistor. The GaAs resistor exhibits very high thermal resistance because of its small size and the lower thermal conductivity [3, 4].

Therefore the DC performance shown in Fig. 1 was not measured isothermally. The temperature inside the resistor changes from one bias point to another. The isothermal IV response was then obtained via pulse measurement. The pulse width and period are 100ns and 10ms, respectively. The measured pulse IV is shown in Fig. 4. As shown in Fig. 4,

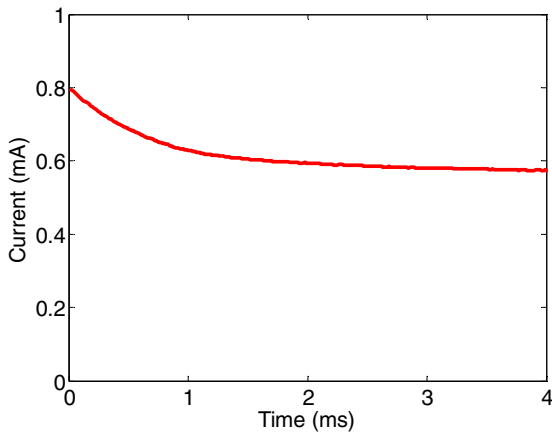


Figure 3. Transient response of resistor A with pulse width of 4ms, pulse period of 10ms, and pulse height of 5V

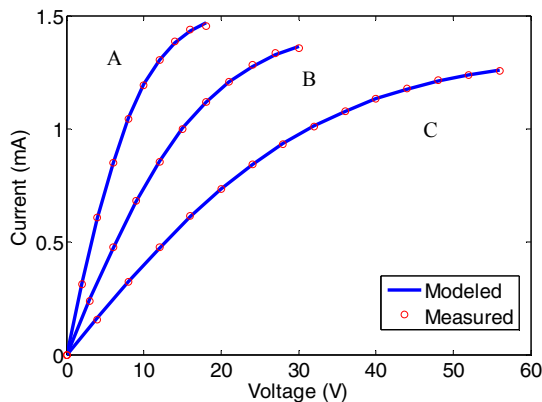


Figure 4. Pulse IV performance of GaAs resistor A, B, and C

excellent agreement can be achieved between the measurement and simulation based on (1).

The extracted saturation currents from both DC and pulse IVs are shown in Fig. 5. The saturation currents from pulse IVs are much higher than those from DC IVs.  $I_S$  can be considered as a measure of the nonlinearity. The smaller the  $I_S$ , the stronger the nonlinearity. The current saturation shown in pulse performance is due to the electron velocity saturation [5], and the current saturation is further enhanced by self-heating effect in DC performance.

The pulse IV measurements were also performed at different temperatures. Fig. 6 shows the temperature dependence of pulse IV for resistor A. The DC IV measured at room temperature is also shown for comparison. It can be clearly seen, from the overlap of pulse and DC IVs, how the resistor temperature changes with bias under DC operation.

#### B. New Model Based on Self-heating Effect

Linear resistance  $R_0$  and saturation current  $I_S$  at different temperatures can be extracted from corresponding pulse IV with (1), and shown in Fig. 7. Linear resistance (saturation current) increases (decreases) with increasing temperature. Expressions describing the temperature dependence of  $R_0$  and  $I_S$  can be extracted from the curves shown in Fig. 7.

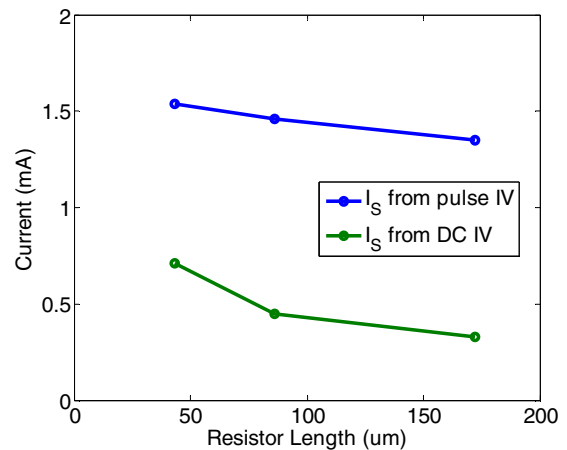


Figure 5. Saturation currents extracted from DC and pulse IVs

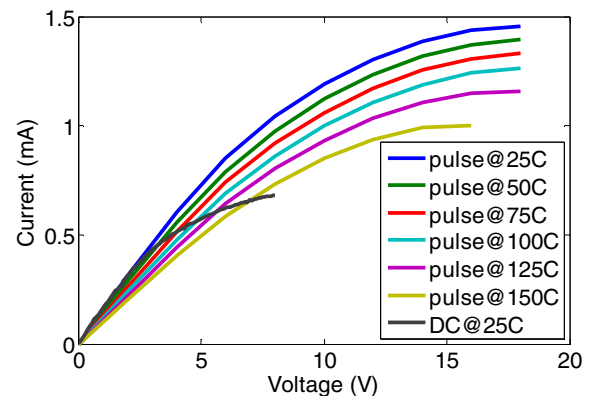


Figure 6. Temperature dependence of pulse IVs for resistor A

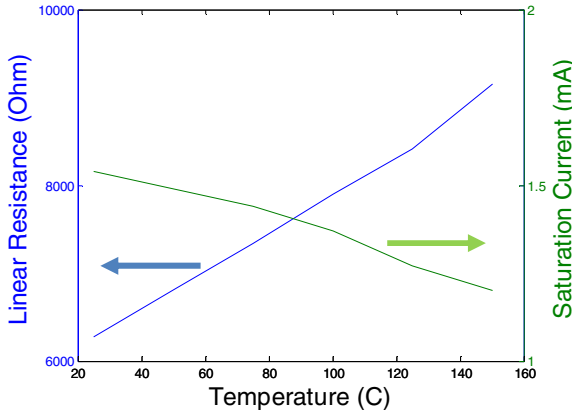


Figure 7. Temperature dependence of linear resistance and saturation current

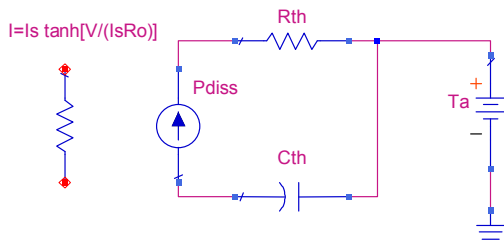


Figure 8. Proposed resistor model taking into account both velocity saturation and self-heating effects

A resistor model based on both velocity saturation and self-heating is then proposed and shown in Fig. 8. The temperature inside the resistor is determined by the ambient temperature and the temperature increase due to the dissipated power,  $\Delta T = T_{amb} + R_{th} P_{diss}$ , where  $R_{th}$  is the thermal resistance of the resistor. The IV behavior can now be expressed as (2). It should be noted that both  $R_0$  and  $I_S$  are now temperature dependent.

$$I = I_S(T) \tanh\left(\frac{V}{R_0(T)I_S(T)}\right). \quad (2)$$

The thermal resistance can be extracted by fitting the DC IV response with the model shown in Fig. 8, and the thermal capacitance can be extracted by fitting the transient response shown in Fig. 3. DC, pulse and transient responses can now be accurately predicted with one model. As an example, Fig. 9 shows the simulated DC IV of resistor A and the temperature inside the resistor.

Fig. 10 shows the comparison between the measured and simulated power performances based on the new model. The harmonic prediction is much better than that shown in Fig. 2. The improvement can be explained as follows. Since the self-heating is a slower process, the nonlinearity associated with

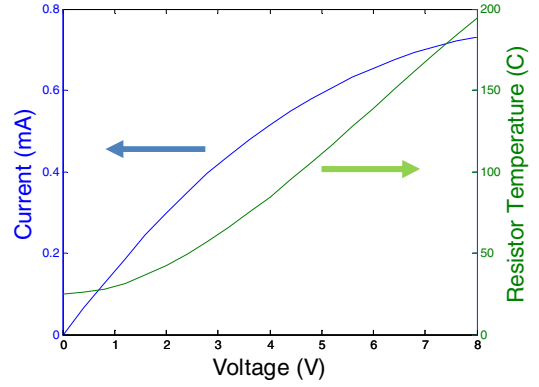


Figure 9. Simulated DC IV of resistor A and the resistor temperature

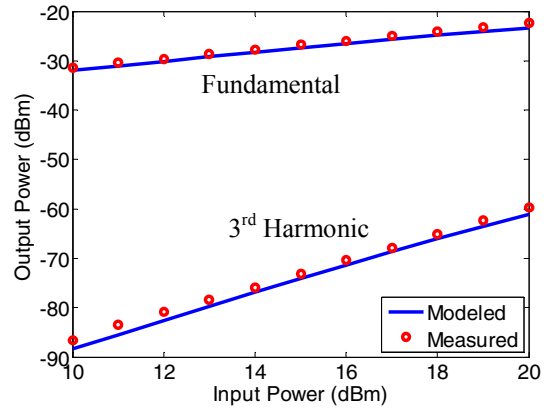


Figure 10. Single tone power performance of resistor B, measurement versus simulation with new model

self-heating, as shown in Fig. 1, has almost no contribution to high frequency performance.

### C. Modeling of Breakdown Behavior

Breakdown behavior is another important aspect of device modeling for ESD protecting circuit and circuit reliability. The breakdown behavior was measured with pulsed voltage. The measured breakdown voltages are around 40 and 60V for resistor A and B, respectively, and no breakdown was observed for resistor C up to 100V. A simple expression, Equation (3), is proposed to predict breakdown behavior with two additional parameters. As shown in Fig. 11, the breakdown behavior can be well described with (3). It is also believed that the breakdown under pulse operation is due to the high electrical field, and that under DC operation, which is observed at much lower voltage, is due the high temperature inside the resistor.

$$I = I_S \tanh\left(\frac{V}{R_0 I_S}\right) + I_b \sinh(\alpha V). \quad (3)$$

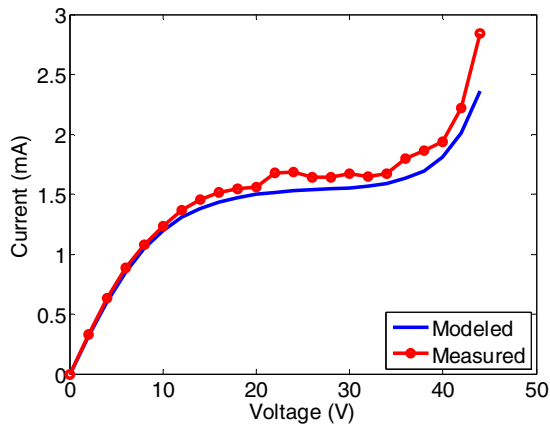


Figure 11. Measured and simulated Breakdown behavior of resistor A under pulse operation

#### IV. SUMMARY

The nonlinearity of a GaAs resistor comes from both velocity saturation and self-heating effects at DC and low frequency, and is dominated by velocity saturation at high frequency. Comprehensive nonlinear model has been developed by taking into account of velocity saturation, self-heating and breakdown effects. The model provides accurate prediction in DC, transient and harmonic balance simulations.

In addition, the breakdown prediction makes the model useful in ESD applications.

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#### REFERENCES

- [1] Yu Zhu; Cejun Wei; Klimashov, O.; Zhang, C.; Tkachenko, Y.; , "Nonlinear model of epitaxial layer resistor on GaAs substrate," *Gallium Arsenide and Other Semiconductor Application Symposium, 2005. EGAAS 2005. European* , vol., no., pp.385-388, 3-4 Oct. 2005.
- [2] Yu Zhu; Cejun Wei; Klimashov, O.; Zhang, C.; Tkachenko, Y.; , "Scalable nonlinear resistor model for GaAs MMIC," *Microwave Conference, 2006. APMC 2006. Asia-Pacific* , vol., no., pp.1539-1542, 12-15 Dec. 2006.
- [3] Sabin, E.; Scarpulla, J.; Yeong-Chang Chou; Shimamoto, G.; , "A technique for electrically measuring the thermal resistance of GaAs bulk resistors," *GaAs Reliability Workshop, 2000. Proceedings* , vol., no., pp.65-69, 2000.
- [4] Steinmann, P.; Beach, E.; Meinel, W.; Chatterjee, A.; Weiser, D.; Bucksch, R.V.; Weidong Tian; , "Simple Analytical Model of the Thermal Resistance of Resistors in Integrated Circuits," *Electron Devices, IEEE Transactions on* , vol.57, no.5, pp.1029-1036, May 2010.
- [5] Houston, P.A.; Evans, A.G.R.; , "Temperature dependence of the high-field velocity of electrons in n GaAs," *Electronics Letters* , vol.11, no.10, pp.210-211, May 15 1975.