

Chapter 1. Physics of Millimeter-Wave Power InAlAs/InGaAs Heterostructure Field-Effect Transistors

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1.1 A New Dynamic Model for the Kink Effect in InAlAs/InGaAs HEMTs

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We present a new model for the dynamic behavior of the kink effect in InAlAs/InGaAs HEMTs. The model suggests that the kink is due to a threshold voltage shift which arises due to hole pileup in the extrinsic source and an ensuing charging of the surface. The model is incorporated in a simple equivalent circuit, which explains well the DC characteristics of the kink and its time evolution in the nanosecond range, as well as its dependence on illumination.

1.1.1 Introduction

There is continuing interest in the origin and consequences of the kink effect in InAlAs/InGaAs HEMTs. The kink is associated with reduced gain and excess noise at high frequencies. While there is mounting

evidence that the kink might be associated with impact ionization and a resulting hole pile-up somewhere in the device, traps are generally invoked to explain the light sensitivity and dynamic behavior of the kink.¹

We have recently carried out a systematic study of the kink, including detailed DC characterization,² sidegate measurements,³ and large-signal transient measurements with nanosecond resolution.⁴ In this work, we have performed these measurements as well as light sensitivity measurements, on the same set of devices. We show that our experimental results can be explained by an impact-ionization based model where hole pile-up at the source shifts the threshold voltage of the device. This has allowed us to develop the first dynamic physical model and a complete equivalent circuit for the kink in InAlAs/InGaAs HEMTs.

1.1.2 Model

We and other researchers⁵ have previously suggested how the kink may arise due to an accumulation of i.i. generated holes in the extrinsic source and an ensuing reduction of the source resistance (R_s). However, R_s reduction is not sufficient to explain the

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- 1 B. Georgescu, M.A. Py, A. Souifi, G. Post, and G. Guillot, "New Aspects and Mechanism of Kink Effect in InAlAs/InGaAs/InP Inverted HFETs," *IEEE Electron Dev. Lett.* 19(5): 154-56 (1998); W. Kruppa and J.B. Boos, "Examination of the Kink Effect in InAlAs/InGaAs/InP HEMTs Using Sinusoidal and Transient Excitation," *IEEE Trans. Electron Dev.* 42(10): 1717-23 (1995).
 - 2 M.H. Somerville, J.A. del Alamo, and W. Hoke, "A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs," *International Electron Devices Meeting Technical Digest*, 1995.
 - 3 M.H. Somerville, J.A. del Alamo, and W. Hoke, "Direct Correlation Between Impact Ionization and the Kink Effect in InAlAs/InGaAs HEMT's," *IEEE Electron Dev. Lett.* 17(12): 473-75 (1996).
 - 4 A. Ernst, M.H. Somerville, and J.A. del Alamo, "Dynamics of the Kink Effect in InAlAs/InGaAs HEMTs," *IEEE Electron Dev. Lett.* 18(12): 613-15 (1997).
 - 5 M.H. Somerville, J.A. del Alamo, and W. Hoke, "A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs," *International Electron Devices Meeting Technical Digest*, 1995; T. Suemitsu, T. Enoki, M. Tomizawa, N. Shigekawa, and Y. Ishii, "Mechanism and Structural Dependence of Kink Phenomena in InAlAs/InGa As HEMTs," *Proceedings of the International Conference on InP and Related Materials*, 1997, pp. 365-68.

kink effect, especially in high-performance devices and close to threshold, where there is little voltage drop on the extrinsic source. Some other effect must be present.

The mechanism we suggest is outlined in Figure 1. An ideal device with a perfect insulating buffer is considered; the device is biased in the saturation regime. To understand the mechanism, we consider how the kink evolves as a function of time if impact ionization is instantaneously “turned on” at $t = 0$. When impact ionization is first turned on, holes are generated in the high-field drain region of the channel. While some of these holes escape through the gate, many of them flow back through the channel of the intrinsic device into the extrinsic source, where they accumulate in the channel.⁶ These holes reach quasi-equilibrium within the channel at the source in about a recombination lifetime (Figure 1b).

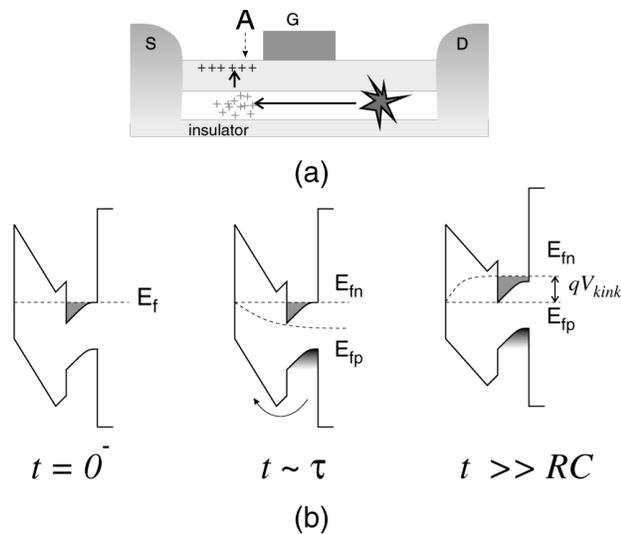


Figure 1. (a) Proposed kink mechanism in ideal device. At $t = 0$, impact ionization is turned on. The energy bands along a vertical slice at A evolve in time as shown in (b).⁷

Reaching equilibrium with the surface takes a longer time. The bending of the hole quasi-Fermi level in the insulator requires a small hole current to the surface, which slowly changes the surface charge and raises the potential of the channel.⁷ This change in channel potential does result in a reduction in source resistance,⁷ but *also* results in a change of the intrinsic device's threshold voltage (Figure 2). To first order,

$$\Delta V_T = V_{\text{kink}} = -\frac{k_B T}{q} \ln\left(\frac{p_0 + p'}{p_0}\right) \quad (1)$$

where p_0 is the “pre-kink” hole concentration in the region next to the source, and p' is the excess hole concentration there, which is linearly related to the impact ionization rate.

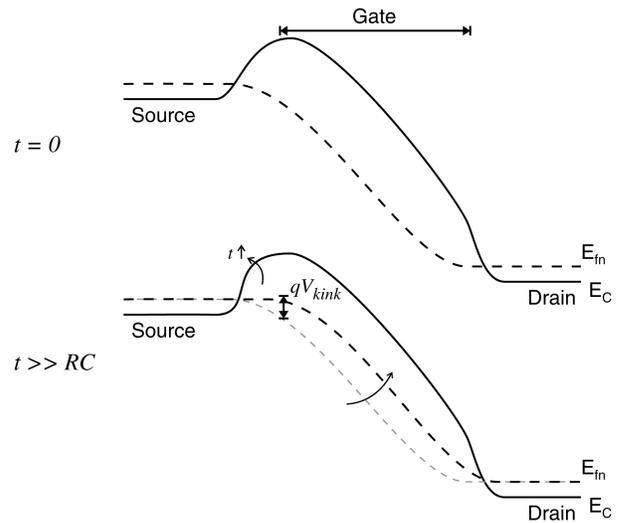


Figure 2. Conduction band along the channel before and after onset of impact ionization. The threshold voltage of the device is modified by an amount V_{kink} .

6 M.H. Somerville, J.A. del Alamo, and W. Hoke, “A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs,” *International Electron Devices Meeting Technical Digest*, 1995; T. Suemitsu, T. Enoki, M. Tomizawa, N. Shigekawa, and Y. Ishii, “Mechanism and Structural Dependence of Kink Phenomena in InAlAs/InGa As HEMTs,” *Proceedings of the International Conference on InP and Related Materials*, 1997, pp. 365-68.

7 T. Suemitsu, T. Enoki, M. Tomizawa, N. Shigekawa, and Y. Ishii, “Mechanism and Structural Dependence of Kink Phenomena in InAlAs/InGa As HEMTs,” *Proceedings of the International Conference on InP and Related Materials*, 1997, pp. 365-68.

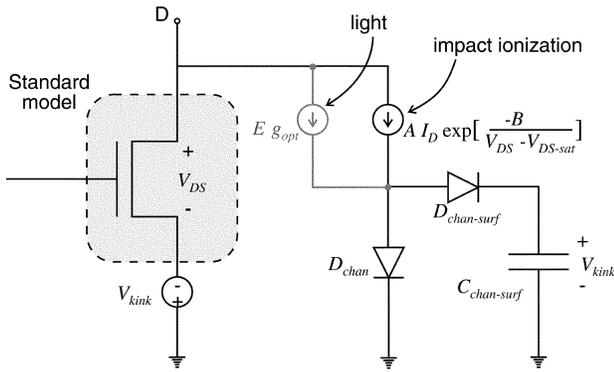


Figure 3. Proposed large-signal transient kink equivalent circuit model. The model consists of an impact ionization current source, a channel diode with unity saturation current, and a surface-to-channel diode and capacitance. Three fitting parameters are needed: A and B in the impact ionization current source, and D , which relates the small signal resistance of the channel surface diode to the impact ionization rate (see text). Also included (in gray) is a bias-independent photogeneration current, $E g_{opt}$, which describes the illumination dependence of the kink.

Given this insight, we can model the behavior of the kink with a simple equivalent circuit (Figure 3) that includes an impact ionization current source and channel diode, which determine the DC behavior of the kink, as well as a channel-to-surface diode and capacitor to model the dynamics. The model contains three bias independent fitting parameters: A and B , which describe the impact ionization rate through the experimentally verified expression

$$I_{ii} = A I_D \exp\left(\frac{-B}{V_{DS} - V_{DS-sat}}\right) \quad (2)$$

and D , which linearly relates the channel-surface RC time constant to the impact ionization rate through

$$RC = \frac{D}{I_D \exp(-B / V_{DS} - V_{DS-sat})} \quad (3)$$

Eq. 1 is, of course, similar to the expression for V_T shift used in SOI models. This should not be surprising, given that in both cases the kink results from

similar physics—impact ionization, hole accumulation, and a Boltzmann-type relationship relating potential to hole accumulation.

It is important to note, though, that the detailed physical origins of the kink in the two models are significantly different—in partially-depleted SOI, the kink arises from forward biasing the source-body junction,⁸ whereas in this model, the kink is a result of hole accumulation in the extrinsic source and the ensuing modification of the surface-channel potential and electron concentration beneath the source end of the gate. While this difference has no impact on the form of the model, it is an important consideration when one attempts to engineer away the kink—if the kink is due to a floating body effect, one might try to suppress it by introducing an additional barrier in the valence band beneath the channel, or by increasing the resistivity of the buffer. On the other hand, if hole pile-up in the extrinsic source causes the kink, approaches such as passivating the surface in the source gate region (thereby relaxing Fermi level pinning) or introducing a hole barrier in the insulator might be more appropriate.

1.1.3 Dynamic Effects

To test this model, we have carried out a systematic set of measurements on InAlAs/InGaAs HEMTs fabricated at MIT. The devices have $L_G = 1.2 \mu\text{m}$ and $2 \mu\text{m}$. These long gate lengths are advantageous to study the kink, as the devices have little intrinsic output conductance. DC and sidegate measurements yielded results similar to M.H. Somerville et al.⁹ and are consistent with the new model. Transient measurements were taken using a pulsed IV setup described elsewhere,¹⁰ these measurements allow us to track the time evolution of the kink throughout the $I_D - V_{DS}$ plane. As can be seen in Figure 4 and Figure 5, the model does an excellent job of describing the kink from its early stages, in which the kink is almost non-existent, through its appearance first at high V_{DS} , and to its later appearance at low V_{DS} . Note that A and B can be determined by the DC and sidegate measurements, so that only *one* additional parameter, D , is used to describe the complete time evolution of the kink.

8 J.P. Colinge, *Silicon-on-Insulator Technology: Materials to VLSI* (Norwell, Massachusetts: Kluwer, 1991).

9 M.H. Somerville, J.A. del Alamo, and W. Hoke, "A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs," *International Electron Devices Meeting Technical Digest*, 1995.

10 A. Ernst, M.H. Somerville, and J.A. del Alamo, "Dynamics of the Kink Effect in InAlAs/InGaAs HEMTs," *IEEE Electron Dev. Lett.* 18(12): 613-15 (1997).

These results are more impressive when one considers the frequency dispersion of the output conductance (Figure 6). Such dispersion has been previously reported¹¹ and is generally associated with traps. Our model makes it clear that the frequency dispersion of the kink can be explained without invoking particular trap characteristics.

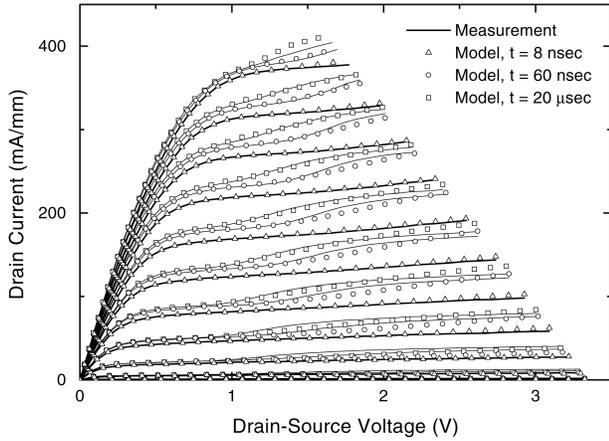


Figure 4. Pulsed I-V curves measured at three different times. Also shown are results from the equivalent circuit model shown in Figure 3. Only three bias-independent constants are required to fit the kink for all the times considered. $T = 300$ K.

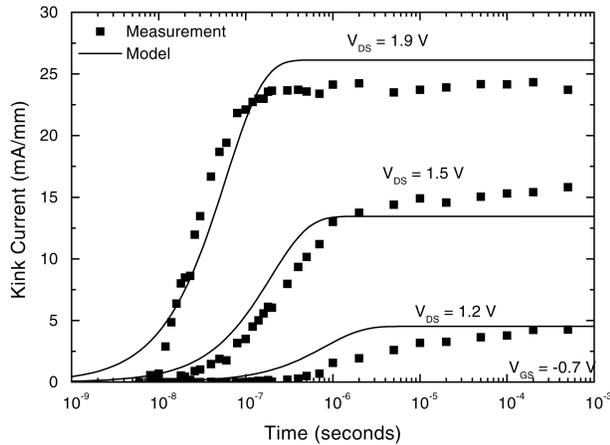


Figure 5. Kink current as a function of time for three different bias conditions, with predictions of the model. $T = 300$ K.

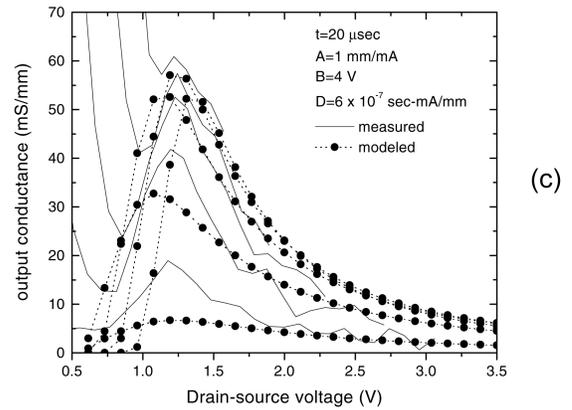
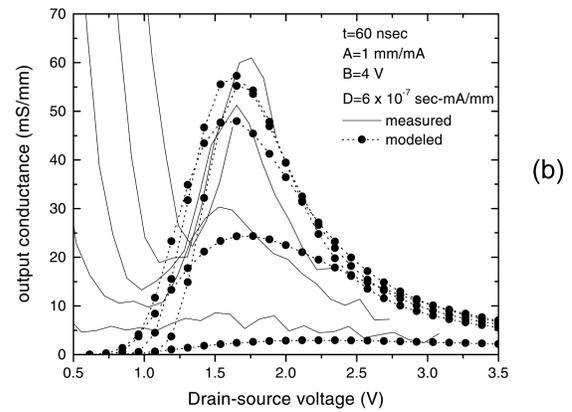
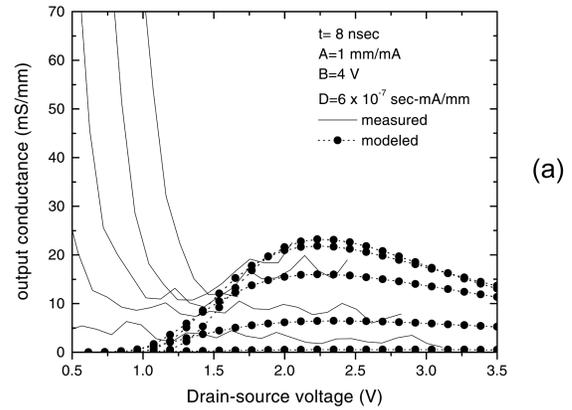


Figure 6. (a) Measured and modeled output conductance for $t = 8$ nsec, (b) $t = 60$ nsec, and (c) $t = 20$ μ sec. Different lines correspond to different values of V_{GS} ($\Delta V_{GS} = 0.1$ V). $T = 300$ K.

11 W. Kruppa and J.B. Boos, "Examination of the Kink Effect in InAlAs/InGaAs/InP HEMTs Using Sinusoidal and Transient Excitation," *IEEE Trans. Electron Dev.* 42(10): 1717-23 (1995).

1.1.4 Illumination

Our model also explains the light dependence of the kink (Figure 7 and Figure 8).¹² Here we have measured the device's output characteristics and transfer characteristics under different levels of illumination with white light at $T = 300$ K, where the kink is better defined. As can be seen, under illumination the kink weakens. Furthermore, the pre-kink current rises under illumination, while the post-kink current changes very little. While this is typically associated with photons emptying trap levels, the behavior is also consistent with a change in the pre-kink hole concentration due to photo-generation, an alternative source of holes.¹³

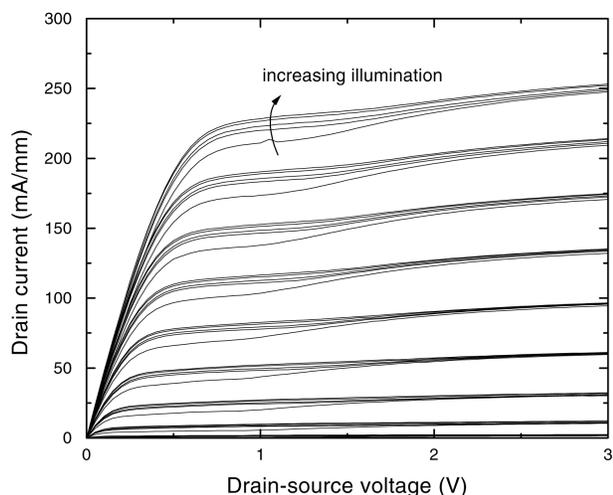


Figure 7. Output characteristics measured with different levels of illumination ($T = 220$ K). The kink disappears as light intensity is increased.

Our model predicts that such optically-generated holes would have the same effect as holes generated by impact ionization—they will accumulate in the extrinsic source, and gradually modify the potential of the channel, yielding a threshold voltage shift as well as a small decrease in the source resistance as suggested by Suemitsu.¹⁴ Both of these effects can be seen in our experiments (Figure 8).

Furthermore, we expect the V_T shift to be logarithmic in the number of excess holes. Under illumination, we expect

$$\Delta V_T = -\frac{K_{BT}}{q} \ln(1 + E g_{opt}) \quad (4)$$

where g_{opt} is the optical generation rate and E is a constant relating the generation rate to the hole concentration in the extrinsic source. As can be seen in Figure 9, ΔV_T is well-described by such an expression.

Thus, it should be possible to model the output conductance both with and without illumination simply by adding a bias-independent current generator to our equivalent circuit model (see Figure 3), where the value of the current is proportional to the optical generation rate. Indeed, as shown in Figure 10, the addition of such a circuit element allows us to model both the light and dark kink output conductance *using identical impact ionization parameters*.

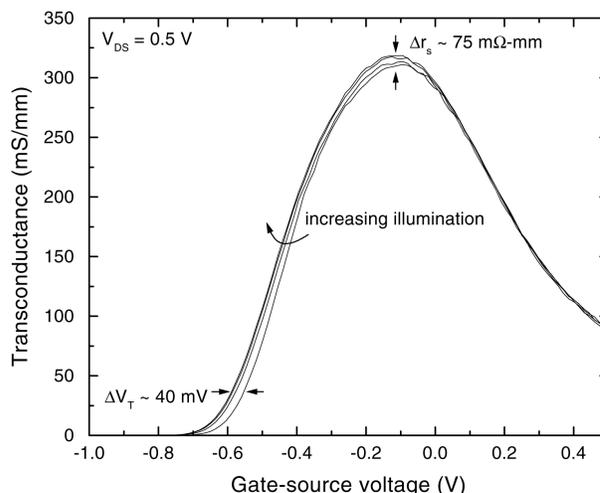


Figure 8. Pre-kink ($V_{DS} = 0.5$ V) transfer characteristics with and without illumination. Under illumination, the device exhibits a threshold voltage shift and reduction in source resistance consistent with increased hole concentration in the extrinsic source. $T = 220$ K.

¹² B. Georgescu, M.A. Py, A. Souifi, G. Post, and G. Guillot, "New Aspects and Mechanism of Kink Effect in InAlAs/InGaAs/InP Inverted HFETs," *IEEE Electron Dev. Lett.* 19(5): 154-56 (1998); Y. Hori and M. Kuzuhara, "Improved Model for Kink Effect in AlGaAs/InGaAs Heterojunction FETs," *IEEE Trans. Electron Dev.* 41(12): 2262-66 (1994)

¹³ Y. Hori and M. Kuzuhara, "Improved Model for Kink Effect in AlGaAs/InGaAs Heterojunction FETs," *IEEE Trans. Electron Dev.* 41(12): 2262-66 (1994).

¹⁴ T. Suemitsu, T. Enoki, M. Tomizawa, N. Shigekawa, and Y. Ishii, "Mechanism and Structural Dependence of Kink Phenomena in InAlAs/InGaAs HEMTs," *Proceedings of the International Conference on InP and Related Materials*, 1997, pp. 365-68.

Finally, our model explains many of the other observed dependencies of the kink. The sensitivity of the kink to surface treatments and gate recess can be understood in terms of the surface pinning condition—as Fermi level pinning at the surface is relaxed due to a reduced number of mid-gap traps, the kink disappears.¹⁵ Similarly, the extension of the recess on the source side of the gate will obviously change the strength of the effect, as has been seen in simulations.¹⁵ The model also explains the observed weakening of the kink with increasing temperature¹⁶ through the strong T-dependence of p_0 .

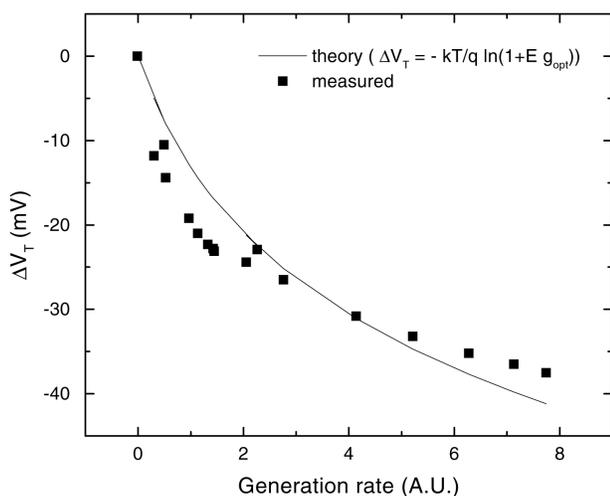


Figure 9. Shift in pre-kink V_T as a function of optical generation rate, as determined by reverse gate current. The device exhibits a V_T shift that is logarithmic in the number of optically generated holes. $T = 220$ K.

1.1.5 Conclusions

In conclusion, we have presented a new physical model for the kink effect in an InAlAs/InGaAs HEMT which explains the kink's DC characteristics, pulse characteristics in the nanosecond range, and its dependence on illumination, surface passivation, and temperature. The physical model is easily captured in an equivalent circuit model which works well for a wide range of time scales and biases.

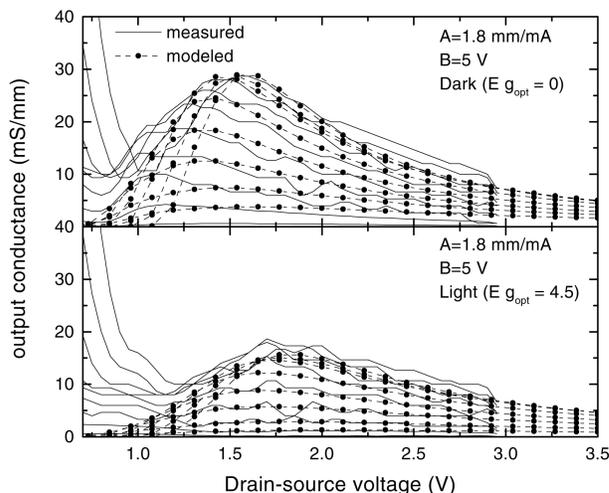


Figure 10. Measured and modeled output conductance with and without illumination. Under illumination, the model explains the output conductance using the same fitting parameters with the addition of a bias-independent hole generation term. $T = 220$ K.

1.2 Publications

1.2.1 Journal Articles

Ernst, A.N., M.H. Somerville, and J.A. del Alamo. "A New Z11 Impedance Technique to Extract Mobility and Sheet Carrier Concentration in HEMTs." *IEEE Trans. Electron Dev.* 45(1): 9-13 (1998).

Somerville, M.H., J.A. del Alamo, and P. Saunier. "Off-State Breakdown in Power PHEMTs: The Impact of the Source." *IEEE Trans. Electron Dev.* 45(9): 1883-89 (1998).

Somerville, M.H., R. Blanchard, J.A. del Alamo, K.G. Duh, and P.C. Chao. "A New Gate Current Extraction Technique for Measurement of On-State Breakdown Voltage in HEMTs." *IEEE Electron Dev. Lett.* 19(11): 405-07 (1998).

1.2.2 Meeting Papers

del Alamo, J.A., and M.H. Somerville. "Breakdown in Millimeter-Wave Power InP HEMTs: A Comparison with PHEMTs." Paper published in the *Proceedings of the IEEE Gallium Arsenide Integrated Circuits Symposium*, Atlanta, Georgia, November 1998, pp. 7-10.

15 T. Suemitsu, T. Enoki, M. Tomizawa, N. Shigekawa, and Y. Ishii, "Mechanism and Structural Dependence of Kink Phenomena in InAlAs/InGaAs HEMTs," *Proceedings of the International Conference on InP and Related Materials*, 1997, pp. 365-68.

16 B. Georgescu, M.A. Py, A. Souifi, G. Post, and G. Guillot, "New Aspects and Mechanism of Kink Effect in InAlAs/InGaAs/InP Inverted HFETs," *IEEE Electron Dev. Lett.* 19(5): 154-56 (1998); M.H. Somerville, J.A. del Alamo, and W. Hoke, "A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs," *International Electron Devices Meeting Technical Digest*, 1995.

del Alamo, J.A., M.H. Somerville, and R.R. Blanchard. "Millimeter-Wave Power InP HEMTs: Challenges and Prospects." Paper published in the *Proceedings of the European Gallium Arsenide and Related III-V Compounds Application Symposium*, Amsterdam, October 1998, pp. 187-92.

Krupenin, S., M.H. Somerville, R.R. Blanchard, J.A. del Alamo, K.G. Duh, and P.C. Chao. "Physical Mechanisms Limiting the Manufacturing Yield of Millimeter-Wave Power InP HEMTs." Paper published in the *Proceedings of the European Gallium Arsenide and Related III-V Compounds Application Symposium*, Amsterdam, October 1998, pp. 533-38.

Somerville, M.H., A. Ernst, and J.A. del Alamo. "A New Dynamic Model for the Kink Effect in InAlAs/InGaAs HEMTs." Paper published in the *Proceedings of the IEEE International Electron Devices Meeting*, San Francisco, California, 1998, pp. 243-46.

