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Neutron Degradation of the I–V Characteristics of AlGaAs/GaAs Modulation-Doped Field Effect Transistors

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A triangular-well, one-subband depletion layer model has been developed which applies over the range of I-V characteristics from subthreshold to saturation, some nine orders of magnitude in source-drain current. The model has been extended to describe neutron degradation of source-drain current and transconductance.

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The dependence of the threshold voltage on acceptor density and neutron fluence of n-channel AlGaAs/GaAs modulation-doped field effect transistors (MODFETs) has been described previously.[1-3] These analyses have, recently, been extended to describe the dependence of MODFET I-V characteristics on acceptor doping density.[4]. In this work, we have extended the theory further to include neutron degradation, due to carrier removal and acceptor introduction, on MODFET I-V characteristics.

It has been previously shown[4] that the applied gate voltage as a function of device geometry, doping densities, and channel charge, n_s, for MODFETs is given by:

$$V_g = V_0 + f(n_s) \qquad (1)$$

where V_0 is the difference between the Schottky barrier height and the sum of the AlGaAs/GaAs band offset, and the potential drop across the doped AlGaAs layer due to the ionized donors. The function $f(n_s)$ may be written as:

$$f(n_s) = (q/\varepsilon)(d + a)(N_aW + n_s) + C_0(N_aW + n_s)^{2/3} + (kT/q)\ln(\exp(n_s/n_c) - 1) \qquad (2)$$

where C_0 is a function of the Planck constant, the carrier effective mass, the elemental charge, and the permittivity of AlGaAs and GaAs, assumed identical. C_0 is equal to $\sim 1.7 \times 10^{-9}$ V-cm$^{4/3}$. Similarly, the charge density n_c is a function of physical constants and the effective mass of the carriers and is equal to $\sim 8.4 \times 10^{11}$ cm^{-2}.

In the charge control model, I-V characteristics are determined by substituting $V_g - V_c(x)$ for V_g in Eq. (1), inverting the result, by using Eq. (2), to find n_s as a function of $V_c(x)$. Then, the current is calculated by substituting the result for $n_s(x)$ in terms of V_g and $V_c(x)$ into the relationship for the current at position x in the channel [$I(x) = q\mu n_s(x)dV_c(x)/dx$; where μ is the mobility], and integrating over the channel length[5]. In the subthreshold and saturation regions, approximations for $f(n_s)$ allow a straightforward inversion of Eq. (1) for this purpose[6,7].

However, there is a region in channel charge density over which neither the subthreshold nor the saturation approximations apply. Because the integration for the current is performed over the voltage in the channel as well as over the channel length, an approximation which is continuous in the voltage may be inverted to explicitly determine the channel charge in terms of the channel voltage, and reasonable approximates of $f(n_s)$ over the region must be determined. To this end we have derived a piecewise approximation for $f(n_s)$ over this region which allows inversion of Eq. (1).

Using this piecewise approximation, the charge control model may be used to calculate the I-V characteristics. A complication arises in the application of the charge control model because, for various values of the applied gate and drain-source voltages, different regions of the channel may have charge densities that must be calculated by different approximations to $f(n_s)$. Therefore, the current equation must be integrated in a piecewise fashion. The results for the drain-source current as a function of drain-source voltage and gate voltage, using the piecewise approximation, have been discussed elsewhere.[4]

Neutron degradation of the I-V characteristics may be accounted for by carrier removal, acceptor introduction, and mobility degradation. The effects of carrier removal and acceptor introduction may be incorporated in the model by substitution of an effective donor density, N_d' and effective acceptor density, N_a', where:

$$N_d' = N_d - a_d \phi \tag{3a}$$

$$N_a' = N_a + a_a \phi \tag{3b}$$

N_a is the pre-irradiation acceptor density, N_d is the pre-irradition donor density, a_d is the carrier removal rate, a_a is the acceptor introduction rate, and is the neutron fluence. The effects of neutrons on mobility may be accounted for by an expression of the form:

$$\mu_f = \mu_i/(1 + K_\mu \phi) \tag{4}$$

where μ_f and μ_i are the post- and pre-irradiation mobilities, respectively, and K_μ is the neutron mobility damage constant. Using Eqs. (3a), (3b), and (4) in our piecewise model yields post-irradiation results for MODFET I-V characteristics from subthreshold to saturation.

We have applied our model to the analysis of the I-V characteristics of neutron-irradiated MODFETs. Shown in Figure 1 is the ratio of the post- to pre-irradiated source-drain current versus neutron fluence. The applied gate and soure-drain voltage was 0.4 volts (the peak of the transconductance) and 2 volts, respectively. Uncertainties on the data represent one standard deviation. Relevant device parameters are listed. The solid straight line is the result of a linear regression analysis of the data. This result is included for comparison to highlight the point that the data and the theory show a nonlinear dependence of the source-drain current degradation on neutron fluence.

The dotted curve is the result of the piecewise I-V model using an acceptor introduction rate of 0.67 cm^{-1} which is consistent with, although slightly higher than, acceptor introduction rates used previously[3]. Mobility degradation was measured by Hall measurement and yielded a value of 2.32×10^{-16} cm^2 for K_μ in Eq. (4). Degradation due to carrier removal, Eq. (3a), is negligible compared to the effects of acceptor introduction and mobility degradation. Closer scrutiny of the theoretical results have shown that at a neutron fluence of 1×10^{15} cm^{-2}, about two-thirds of the degradation is due to mobility degradation and that the remainder is due to acceptor introduction in the GaAs channel.

Shown in Figure 2 are the theoretical and experimental results for the ratio of the post- to pre-irradiation transconductance vs neutron fluence nonlinear dependence of neutron fluence. About two-thirds of the transconductance degradation at a fluence of 1×10^{15} cm^{-2} is due to a decrease in the mobility, which is consistent with the source-drain current degradation. The remainder of the degradation is due to acceptor introduction.

The theoretical results fit the data remarkably well even though we have neglected source and drain resistances in this first order version of the model. We expect that inclusion of the source and drain resistances will

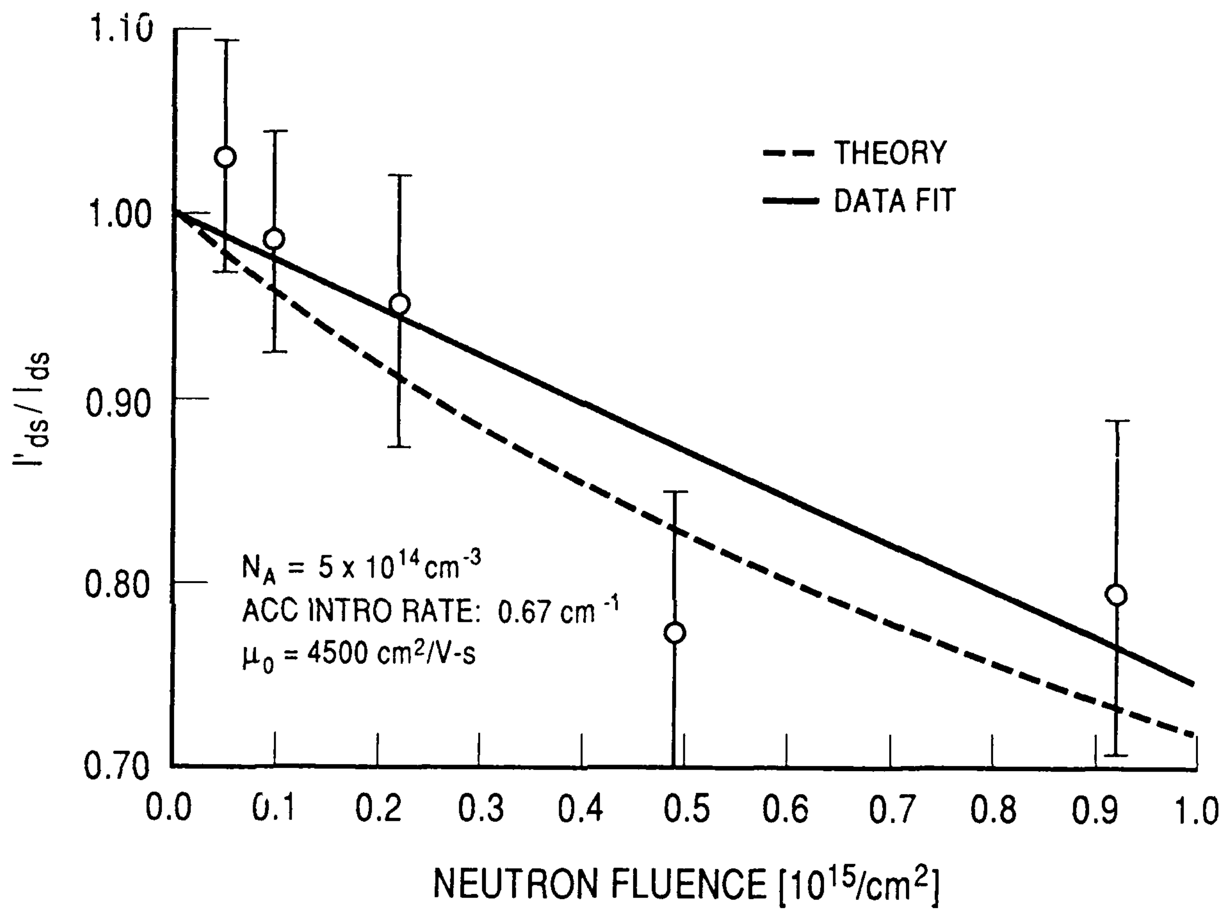

Figure 1. Ratio of Post- to Pre-irradiation Source-Drain Current vs Neutron Fluence. The solid line is a linear fit to the data. The dotted line represents the theoretical results using the triangular-well, one-subband, depletion layer model. This model has been extended to describe I-V characteristics from subthreshold through saturation and includes neutron degradation due to carrier removal and acceptor introduction.

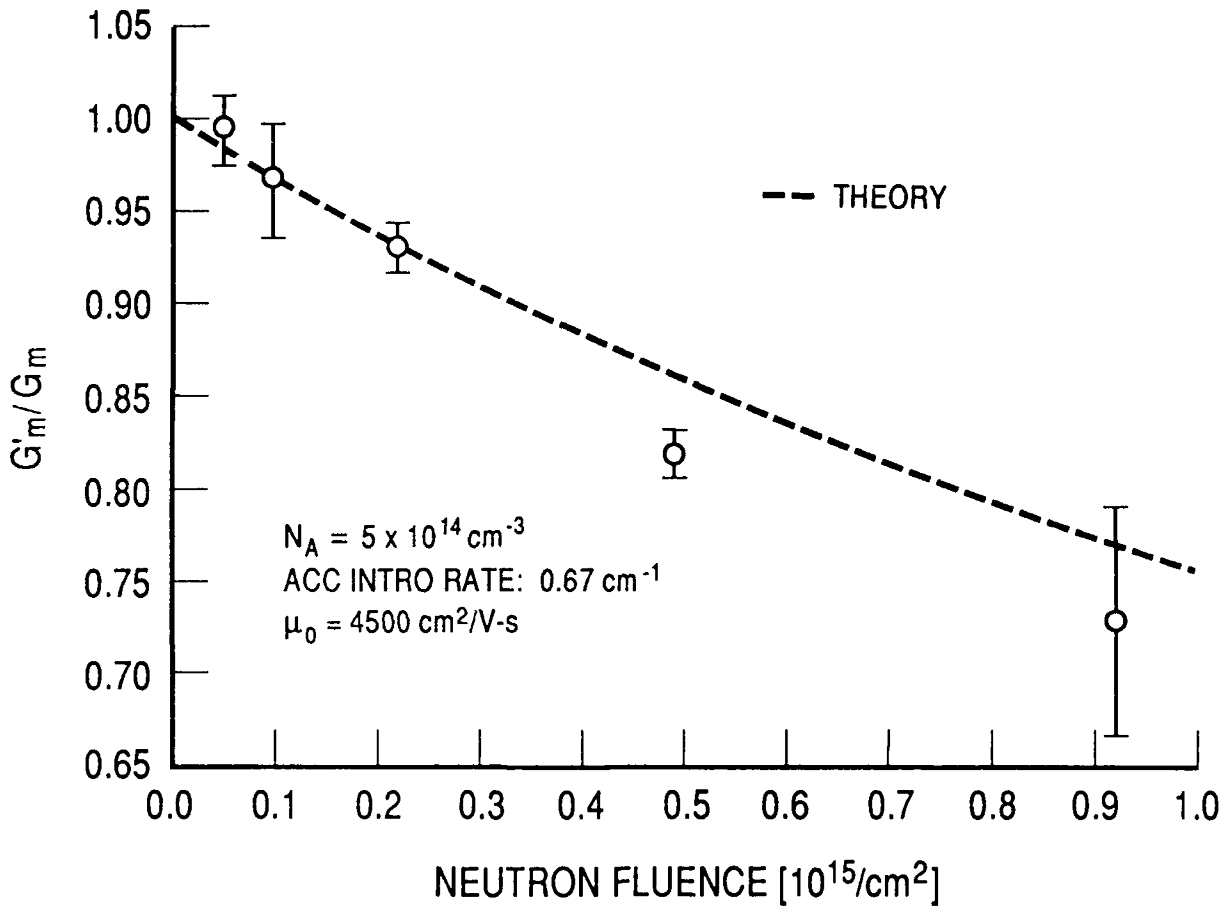

Figure 2. The Ratio of the Post- to Pre-irradiation Transconductance vs Neutron Fluence. The dotted line is the output of the zero source-drain resistance model described in the text.

improve the theoretical results, especially in the high fluence region. The reason for this is shown in Figure 3, in which we have plotted the source-drain resistance vs neutron fluence (and in the insert the end resistance vs fluence). As the neutron fluence increases so does the resistance (the solid lines are parabolic fits to data included to guide the eye). We expect, therefore, the theoretical curves in Figures 1 and 2 to show more degradation, due to the increased resistance, particularly at the higher fluences. Therefore, the data may be simulated using a lower acceptor introduction rate, which is more in keeping with the value of 0.5 cm^{-1} cited in the literature.

Also, pre-irradiation theoretical I-V characteristics will improve. For example, the zero resistance model predicts a pre-irradiaton current of ~8 mA for the bias conditions considered. The experimental results yield a value of ~2 mA. Including source and drain resistance will decrease the theoretical results in keeping with the experimental pre-irradiation results. We are in the process of including source and drain resistances in both the pre- and post-irradiation model.

In summary, we have developed a piecewise MODFET model that may used to describe I-V characteristics of these devices from subthreshold through saturation. The model has been extended to describe neutron degradation of MODFET I-V characteristics. We are unaware of any attempts to model the I-V characteristics of these devices over the whole range of bias conditions, much less include neutron degradation from subthreshold to saturation.

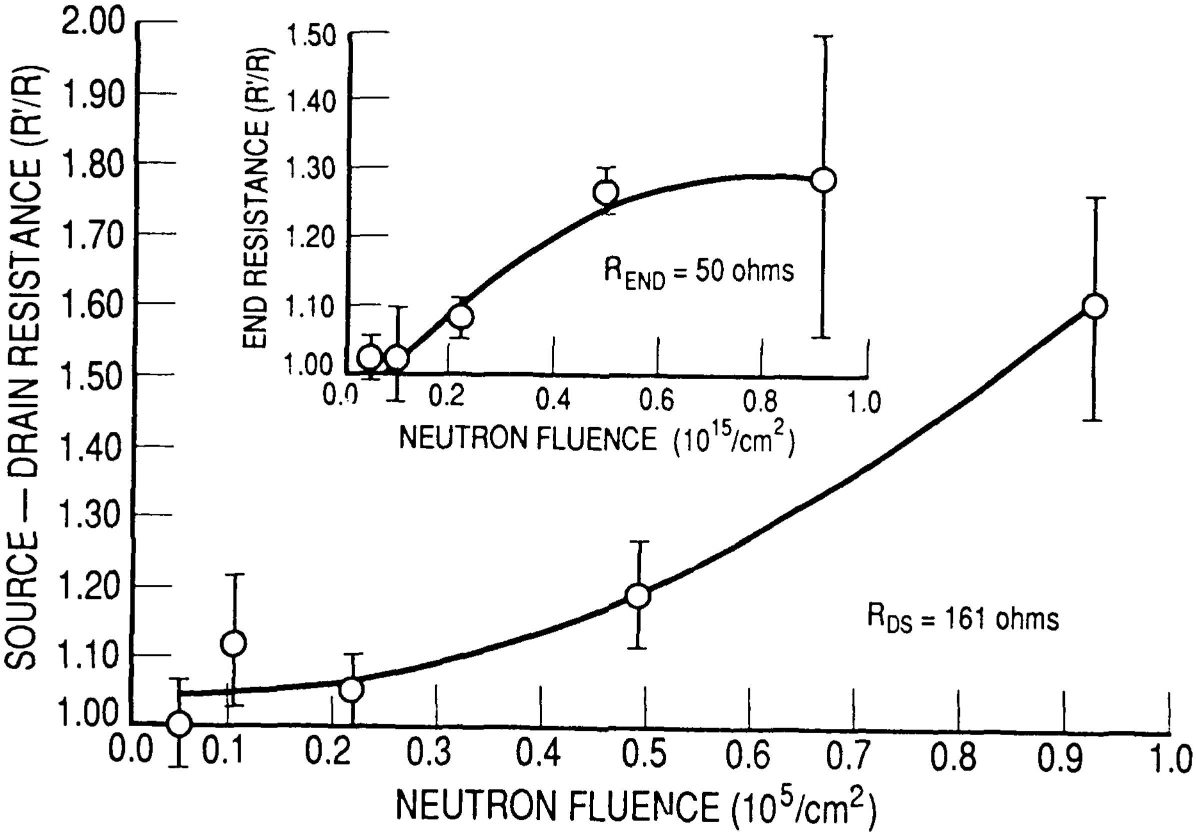

Figure 3. The Source-Drain Resistance vs Neutron Fluence. (Insert: the end resistance vs neutron fluence.)

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