Model for the Bipolar Amplification Effect

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2021 IEEE International Integrated Reliability Workshop (IIRW) | 978-1-6654-1794-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/IIRW53245.2021.9635616

***Abstract*—We present a model based on Fitzgerald-Grove surface recombination for the bipolar amplification effect (BAE) measurement, which is widely utilized in electrically detected magnetic resonance (EDMR) to measure reliability and performance-limiting interface defect structure in metal-oxide-semiconductor field-effect transistors (MOSFETs). This proof-of-concept work illustrates that quantitative BAE measurements can be made to determine interface defect densities and allows for predictions of optimal EDMR BAE biasing. Furthermore, this work also provides an initial step forward for a theory based on spin-dependent recombination measurements utilizing BAE EDMR.**

***Index Terms*—Defect Density, Surface recombination, BAE, MOSFETs**

I. INTRODUCTION

The direct current-current-voltage (dc-IV) [1] technique, which is utilized for Si/SiO$_2$ interface defect density measurements in metal-oxide-semiconductor field-effect transistors (MOSFETs) [2], relies on surface recombination theory developed by Fitzgerald and Grove [1]. Furthermore, electrically detected magnetic resonance (EDMR) measurements based on dc-IV have been utilized to analyze interface defect structure. Recent theoretical work by Harmon $et\ al.$ have linked the Fitzgerald-Grove surface recombination theory to spin-dependent recombination (SDR) theory in order to model both dc-IV EDMR and near-zero field magnetoresistance (NZFMR) measurements [3]. Recently, an EDMR method called the bipolar amplification effect (BAE) was developed, which greatly improves the sensitivity and selectivity of EDMR measurements in MOSFETs [4]. The BAE EDMR scheme is very useful in material systems which have a large number of bulk defects, such as 4H-SiC/SiO$_2$, which would obscure results from a dc-IV EDMR scheme. BAE overcomes this limitation and is sensitive to only the interface. Here, we develop a model for BAE [4] based on the Fitzgerald and Grove surface recombination model [1].

In dc-IV, the source and drain are both held at a slight forward bias V_F with a gate voltage V_G such that the MOS interface is in depletion. The current is measured through the body. When the interface electron and hole densities are equal, there is a peak in the body current corresponding to maximized recombination. From this peak, interface trap densities D_{it} can be extracted through an analytical model of the peak amplitude [1]. In dc-IV EDMR, one would bias the MOSFET such that the device operates on the peak of the body current in order to maximize SDR. BAE involves a similar biasing scheme but the source is forward biased well past the source/body junction built-in voltage with the drain current measured, which is at a potential of 0 V. The body is grounded and the gate is biased such that the MOS interface is in depletion. Figure 1 (a) shows a cartoon illustration of the dc-IV biasing scheme and (b) shows the BAE biasing scheme. In EDMR measurements, this yields a large gain in sensitivity [4].

II. MODEL

Our modified model invokes the recombination rate equation of Fitzgerald and Grove [1]. The physics is very sim-

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The authors would like to thank Fedor Sharov for assistance in technical discussions and sample work and David R. Hughart and Gaddi S. Haase of Sandia National Laboratories for providing the samples utilized in this work.

This project was sponsored by the Department of Defense, Defense Threat Reduction Agency under grant number HDTRA1-18-0012. The content of the information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred.

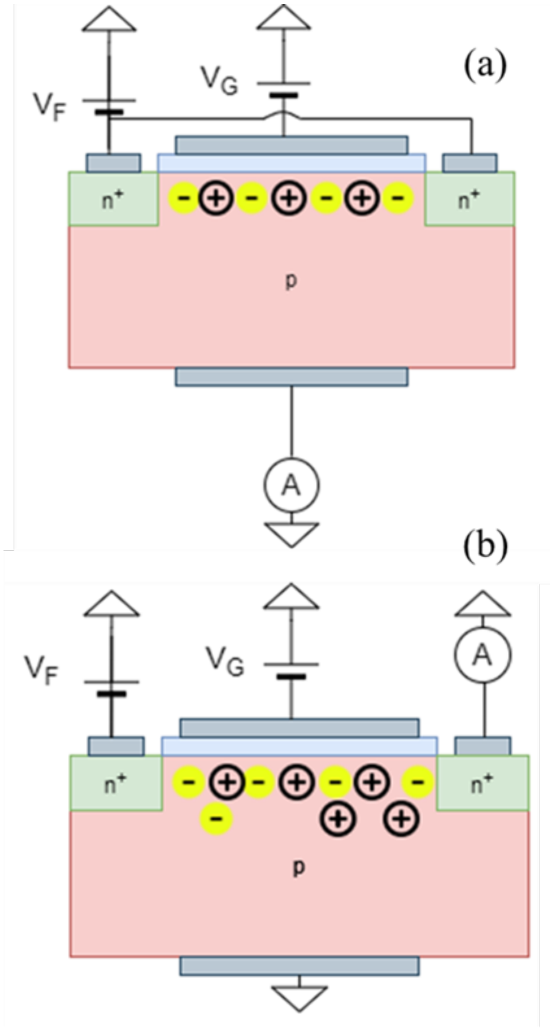

Fig. 1. Illustration of (a) dc-IV biasing scheme with both source and drain forward biased with V_F and gate biased at V_G. Here, the current is measured through the body. (b) BAE biasing scheme with the source forward biased with V_F and gate biased at V_G. Here, the current is measured through the drain and the body is grounded.

ilar to dc-IV. However, since BAE involves the source at a potential V_F and the drain at a potential of 0 V, there will be an electron concentration gradient at the interface. In the following, we show our calculations of the BAE current for n-channel MOSFETs. Mirror expressions would be applicable to p-channel MOSFETs. First, we show the electron and hole concentrations at each side of the MOSFET channel as [5]:

$$\delta n_s(L_C) = n_s(L_C) - n_s = 0, \tag{1a}$$

$$\delta n_s(0) = n_s(0) - n_s = \frac{n_i^2}{n_A} e^{\frac{q\phi_s}{kT}} (e^{\frac{q(V_F)}{kT}} - 1). \tag{1b}$$

$$p_s = n_A e^{\frac{-q\phi_s}{kT}}. \tag{1c}$$

Here, L_C is the channel length, n_s is the surface electron concentration at equilibrium, n_i is the intrinsic carrier concentration (10^{10} cm^{-3} for Si at room temperature), n_A is the acceptor concentration of the body, ϕ_s is the semiconductor band bending close to the interface (which is related to gate voltage V_G), k is Boltzmann's constant, T is absolute temperature, and V_F is the forward bias applied to the source/body junction.

Assume that x is the distance into the channel and is 0 at the source and L_C at the drain. We may utilize solutions to the ambipolar transport equation to find $\delta n(x)$ [5]:

$$D_n \frac{d^2 \delta n_s}{dx^2} - \frac{\delta n_s}{\tau} = 0. \tag{2}$$

Here, τ is the minority carrier lifetime. Utilizing (1) with solutions to (2), $\delta n(x)$ is well described by [5]:

$$\delta n_s(x) = n_s(e^{\frac{qV_F}{kT}} - 1) \frac{\sinh\left(\frac{L_C - x}{L_n}\right)}{\sinh\left(\frac{L_C}{L_n}\right)}. \tag{3}$$

Here, $L_n = \sqrt{\tau D_n}$ is the minority carrier diffusion length (D_n is the electron diffusion coefficient). Thus, the surface electron concentration is $n_s(x) = \delta n_s(x) + n_s$ where $n_s = \frac{n_i^2}{n_A} e^{\frac{q\phi_s}{kT}}$ is the surface concentration far away from the source. If we assume that $L_n \gg L_c$, equation 3 has a linear form that is independent of L_n:

$$\delta n_s(x) = n_s(e^{\frac{qV_F}{kT}}) \left(1 - \frac{x}{L_C}\right). \tag{4}$$

We may utilize (3) with the recombination rate U_S, which is given by [1]:

$$U_S = \sigma_S v_{th} kT D_{it} \left[\frac{\cosh^{-1}\left(\frac{p_s + n_s}{2n_i}\right)}{n_i \left[\left(\frac{p_s + n_s}{2n_i}\right)^2 - 1\right]^{\frac{1}{2}}} \right] [p_s n_s - n_i^2]. \tag{5}$$

Here, σ_s is the electron and hole capture cross section [1], v_{th} is the thermal velocity for both electrons and holes, and D_{it} is the density of interface states. To calculate the BAE current, one would utilize $I = qAU_S$. However, because U_S is a function of x, we utilize integration to establish a mean value of recombination rate over the interface. Thus, the BAE current is well described by:

$$I_{BAE} = qA_G \frac{1}{L_C} \int_0^{L_C} U_S(V_G, V_F, x) dx. \tag{6}$$

III. EXPERIMENTAL DETAILS

The MOSFET samples utilized are n-channel MOSFETs with 1 μm × 15 μm gate areas with 126 transistors chained together. The effective channel length for each sample is 1 μm. The gate oxides for the devices are 7.5 nm thick SiO_2; the gate leakage current is practically zero. The MOSFETs were high field stressed with gate voltage -9.5 V for 20 minutes, resulting in a large increase in D_{it}. The BAE measurements were performed on a semiconductor parameter analyzer. The uncertainty in peak heights of the electrical curves is no greater than 3%. All measurements were performed at room temperature.

TABLE I
DEFECT DENSITIES FROM CP, DC-IV, AND BAE

CP	dc-IV	BAE
1.9×10^{12}	1.7×10^{12}	1×10^{12}

*All densities are reported in units of $cm^{-2}eV^{-1}$.

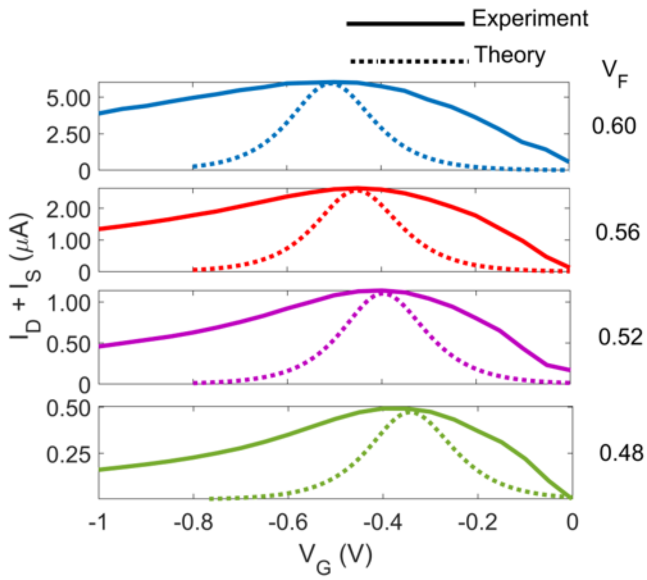

Fig. 2. Experimental BAE response (solid) and our model (dashed) for source voltage four source voltages V_F. The drain and source current have been subtracted since the drain current rises steeply close to the inversion point.

IV. RESULTS AND CONCLUSIONS

Fig. 2 illustrates our model applied to experimental BAE data from measurements performed on the Si MOSFETs. The BAE curves are taken at 0.48 to 0.60 V source voltage in 0.04 V increments. The differences in line shape of the experimental and theory curves can be explained by microscopic nonuniformities of the surface potential caused by a random distribution of surface charges [1]. From these curves, a defect density of 1×10^{12} cm^{-2}eV^{-1} is extracted. We also performed dc-IV measurements in which a defect density of 1.7×10^{12} cm^{-2}eV^{-1} is extracted. In order to verify our measurements, we also performed charge pumping measurements. [6]. The results from the charge pumping measurements yield $D_{it} \approx 1.9 \times 10^{12}$ cm^{-2}eV^{-1}. Note the close correspondence between D_{it} extracted through all three techniques. Table I shows the defect densities from all three measurements.

In Fig. 3(a), we plot our modified surface recombination model and the original Fitzgerald-Grove model. We compare dc-IV curves and BAE curves taken at $V_F = 0.48$ to 0.60 V (in 0.04 V increments) in Fig. 3(b). Note the close correspondence between the trend of the data and simulated data (the dc-IV peaks are larger that the BAE peaks for all V_F, which is predicted with our model in comparison with the original Fitzgerald-Grove model). Our model predicts that the BAE peaks are $\approx \frac{2}{3}$ the size of the dc-IV peaks. The measured ratios of the peaks are about 0.55. We assume a linear concentration of surface electrons in our model (4), similar to a narrow base BJT. To the extent that the linear approximation is incorrect, the predicted $\frac{2}{3}$ would tend to be smaller. It should be noted that both dc-IV and BAE work well with their respective models (Fitzgerald-Grove [1] and our model).

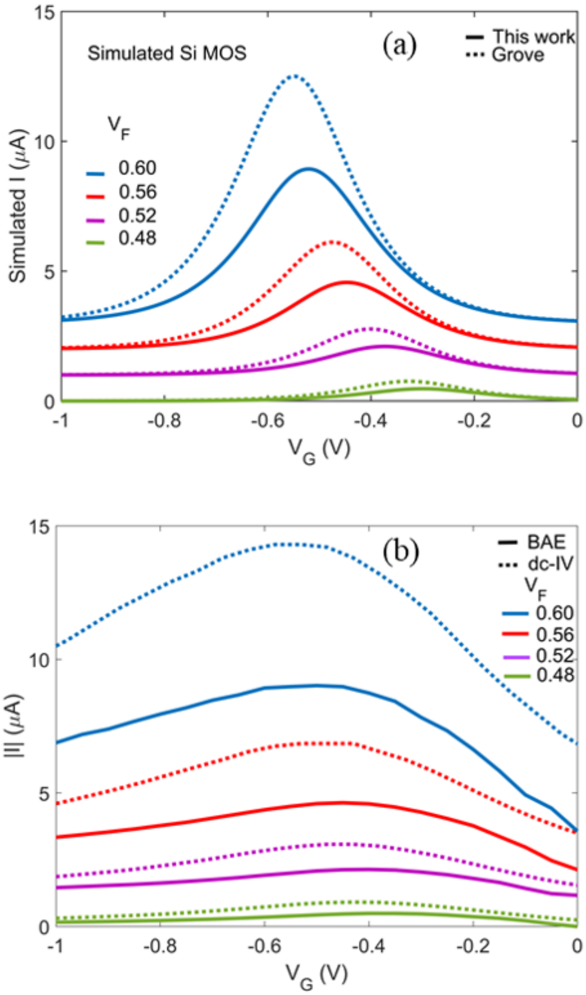

Fig. 3. (a) Fitzgerald-Grove theory (dashed) and our model (solid). (b) dc-IV measurements (dashed) and BAE measurements (solid) performed on the Si MOSFETs at four different forward bias voltages.

Figure 4 shows the experimental and simulated ratio I_{BAE}/I_{dc-IV} as a function of V_F. Note that both theory and experimental ratios are fairly independent of V_F. As mentioned previously, the differences between the modeled and experimentally determined ratios stems from a linear approximation ($L_n \gg L_C$). Thus, from inspection of Fig. 4, it is clear that the model described here demonstrates the independence of I_{BAE}/I_{dc-IV} with V_F. It should be noted that the theoretically determined I_{dc-IV} utilized the original Fitzgerald-Grove model [1]. The values of V_F chosen here were arbitrarily chosen. The V_F values may be smaller

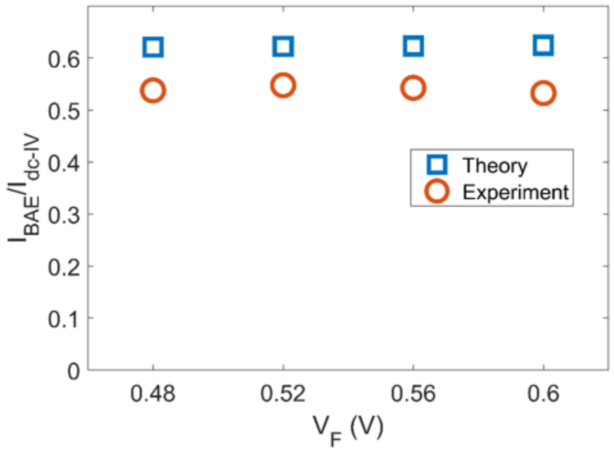

Fig. 4. Modeled (squares) and experimentally determined (circles) ratio I_{BAE}/I_{dc-IV} as a function of forward bias V_F.

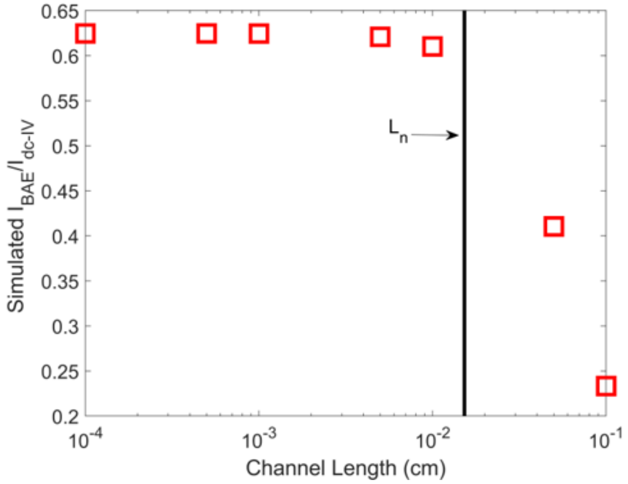

Fig. 5. Modeled ratio I_{BAE}/I_{dc-IV} as a function of channel length L_C with L_n calculated utilizing τ = 30 μs [7]

or larger. However, one should consider semiconductor bulk defect contributions and high level injection effects from smaller or larger values of V_F, respectively.

An interesting prediction of the model described in this work is the dependence of U_S with channel length and L_n. When $L_n \gg L_C$, the distribution of surface electrons is linear. However, if $L_n \ll L_C$, the distribution follows an exponential decay $e^{\frac{-x}{L_n}}$. Thus, one would expect U_S to decay for channel lengths exceeding L_n. Thus, the ratio I_{BAE}/I_{dc-IV} would also tend to decay. In Fig. 5, we plot modeled I_{BAE}/I_{dc-IV} as a function of channel length L_C. Note that when L_C is well below L_n, the ratios are independent of L_C. However, when L_C approaches and exceeds L_n, the ratios begin to decay. One may describe this physically by the following. If $n_s(x)$ decays very fast as would be the case with an exponential decay, less electrons and holes throughout the channel region contribute to the recombination rate. However, if the decay is linear, more electron-hole recombination would contribute to U_S. In both cases, the electron concentration is less than that in dc-IV because in dc-IV, both source and drain are utilized to inject carriers into the channel and are both at the same potential. Thus, the interface is in quasi-equilibrium and no channel-dependent decay of electrons is present.

We have developed a surface recombination model utilizing a modified Fitzgerald-Grove [1] framework. This surface recombination model for BAE enables defect density measurements in MOSFETs utilizing BAE. The model can also serve as a reference for optimizing conditions for BAE EDMR measurements, which has been the core application of BAE since its inception. The surface recombination model may now also serve as a reference in the development of BAE EDMR/NZFMR theories, similar to the recent implementation of SDR theory utilizing Fitzgerald-Grove surface recombination [3]. The model also predicts the dependence of the BAE peak amplitudes with channel length. Through this dependence, BAE may be useful in measuring minority carrier lifetimes at MOSFET surfaces. Future work will entail expanding this work to other systems (4H-SiC), experimentally verifying the predictions of this model regarding channel length-dependent BAE peak amplitudes, and utilizing the model to develop a spin-based BAE model for EDMR measurements.

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