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Note Clarifying the Paper, "Charge Sheet Super Junction in 4H-Silicon Carbide: Practicability, Modeling and Design"

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ABSTRACT This note clarifies an important approximation used to simulate the breakdown field in the SiO_2 liner of a SiC Charge-Sheet Superjunction - a new power device structure - reported by Akshay and Karmalkar (2020). This electric field simulation sought to assure that the new device does not suffer from SiO_2 reliability problems. The note answers two questions: (a) Why do we remove the SiO_2 liner which is the very region of our interest during device simulation, when a simulator allows inclusion of such a region? (b) How can one solve for the field in a region (SiO_2 in the present case) by neglecting that very region during device simulations? Our note reinforces the insight – "Modeling is the art of making approximations."

INDEX TERMS 4H-SiC, breakdown voltage, specific on-resistance, TCAD simulation, analytical model.

I. INTRODUCTION

This note is related to an accompanying paper [1] which discussed the practicability, modeling and design of a variation of the Superjunction (SJ) called the Charge Sheet SJ (CSSJ) in 4H-Silicon Carbide (SiC) material (see Fig. 1(a)). Here a thin Al_2O_3 layer deposited on a thermally grown SiO_2 liner in an etched trench replaces the p-pillar of the SJ. The Al_2O_3/SiO_2 interface has a negative fixed charge of magnitude N_I which acts like the ionized dopant charge of the p-pillar and can be controlled via the Al_2O_3 deposition temperature.

In any SiC power device operating in the OFF state, when the bias is raised, the field in SiO_2 can exceed its critical field of $\sim$ 5 MV/cm well before the field in SiC reaches its critical value of $\sim$ 3 MV/cm, if the field at the SiO_2/SiC interface has a significant normal component. This is because, as per Gauss's law, the normal field in SiO_2 is $\varepsilon_{SiC}/\varepsilon_{SiO2} \approx 2.5$ times of that in SiC, where ε_{SiC} and ε_{SiO2} are the dielectric constants of SiO_2 and SiC. Hence, while designing SiC power devices containing a SiO_2 layer, it is important to ascertain by 2D/3D numerical simulation that the field in the SiO_2 layer remains well below $\sim$ 5 MV/cm when the SiC region breaks down. Accordingly, Fig. 3(c) of [1] which is reproduced here as Fig. 2(a), reported the simulated resultant field, $E_{R,SiO2}$, in the SiO_2 layer of our proposed CSSJ when the SiC region of this device breaks down, and confirmed that this $E_{R,SiO2}$ remains well below 5 MV/cm. It is the purpose of the present note to clarify an important approximation employed in [1] to simulate $E_{R,SiO2}$.

II. THE APPROXIMATION

Instead of simulating $E_{R,SiO2}$ in the actual structure of Fig. 1(a) directly, we simulated the field distribution in the structure shown in Fig. 1(b), where the SiO_2 layer was removed and N_I was placed at the Al_2O_3/SiC interface. From this distribution, which is reproduced here in Fig. 2(b) from Fig. 3(a) of [1], we obtained the fields $E_{y,SiC}$ and $E_{x,SiC}$ in SiC that are parallel and normal to the vertical Al_2O_3/SiC interface (see Fig. 2(a)). Then, we derived $E_{R,SiO2}$ shown in Fig. 2(a) by applying Gauss law as per which E_y is continuous across the vertical SiO_2/SiC interface while the field E_x in SiO_2 is $\varepsilon_{SiC}/\varepsilon_{SiO2} \approx 2.5$ times that in SiC, so that

$$E_{R,SiO2} = \sqrt{E_{y,SiC}^2 + \left(2.5E_{x,SiC}\right)^2}. \quad (1)$$

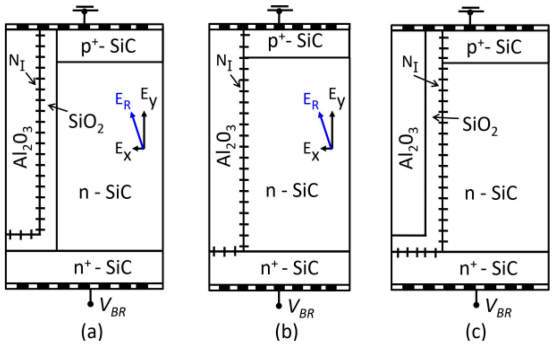

FIGURE 1. **(a) Cross-section of the unit cell of the proposed Charge-Sheet SuperJunction [1]. Diagram not to scale; the actual SO_2 liner is much thinner than shown. (b) A variation of (a) with SiO_2 liner removed. (c) A variation of (a) with the negative interface charge N_I moved to the SiO_2/SiC interface.**

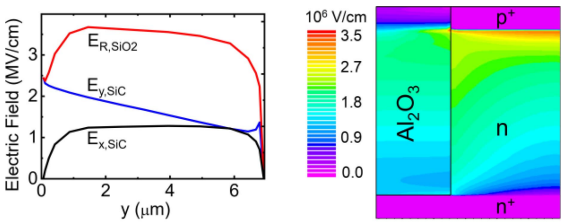

FIGURE 2. **Simulations at breakdown in a 4H-SiC Charge-Sheet SuperJunction with $W_n = 0.7$ μm, $W_I = 0.5$ μm, $L = 7$ μm, $N_d = 1 \times 10^{17}$ cm^{-3}, $N_I = N_d W_n = 7 \times 10^{12}$ cm^{-2} and $V_{BR} = 1$ kV; reproduced from [1]. (a) Components of the n-pillar field ($E_{y,SiC}$ and $E_{x,SiC}$) and the resultant field in SiO_2 liner ($E_{R,SiO2}$) along the vertical Al_2O_3/SiC interface, over the pillar length, L. (b) Field contours.**

The motivation for and the validity of the above approximate procedure are explained below. We did not consider the $E_{R,SiO2}$ along the horizontal SiO_2/SiC n^+ region interface, since this field would be rather low, as anticipated from the $\sim$ 1 MV/cm field along the Al_2O_3/SiC n^+ region interface in Fig. 2 (b).

First, we answer the question: Why do we remove the SiO_2 liner which is the very region of our interest during simulation, when a simulator allows inclusion of such a region? The Silvaco device simulator [2] employed by us can simulate the Al_2O_3 / SiO_2/SiC system of Fig. 1(a) but only *without* the interface charge, N_I, This is because N_I happens to be at Al_2O_3 / SiO_2 which is an insulator / insulator interface, and the simulator does not allow placing of a charge at an insulator / insulator interface. Hence our device structure cannot be simulated as it is. However, the simulator allows the placing of an interface charge at a semiconductor / insulator interface such as Al_2O_3/SiC in Fig. 1(b) or SiO_2/SiC in Fig. 1(c). Hence, the variations Fig. 1(b),(c) of the actual structure of Fig. 1(a) can be simulated. However, the field in the SiO_2 layer of Fig. 1(c) will not be the same as that of Fig. 1(a); this is because, unlike the SiO_2 layer of Fig. 1(a), the SiO_2 layer of Fig. 1(c) will not experience the field lines which emanate from the ionized donors of n-SiC and terminate on N_I. Hence, we need to work with the structure of Fig. 1(b) in simulations.

Next we answer the question: How can one solve for the field in a region (SiO_2 in the present case) by neglecting that very region during the simulations? This is possible if the field in the region of interest depends on that in another region of the device, whose field is however negligibly dependent on the region of interest. Consider an analogy: we can solve for x in the following equation

$$e^x = 1000 + x \tag{2}$$

by neglecting the very x to be solved for on the RHS, because contribution of x to the RHS is small, i.e., $x << 1000$; this is confirmed from the fact that $x = \ln 1000 = 6.91$ obtained by this approach is indeed only 0.691% of 1000. Yet another analogy is the derivation of the text book ideal diode equation

$$I = I_0\left(e^{V/Vt} - 1\right) \tag{3}$$

where I_0 is the reverse saturation current and V_t is the thermal voltage. This equation is based on the law of the junction, namely – at applied bias V, the minority carrier concentration at the depletion edge is $e^{V/Vt}$ times the equilibrium concentration at the same location. This law is derived by neglecting the very I to be solved for compared to the average drift and diffusion currents over the depletion width. Apart from this quasi-equilibrium approximation, the quasi-static and quasi-neutrality approximations commonly employed in semiconductor device modeling can also be shown to follow the approach of neglecting the very quantity being solved for somewhere in the initial stages of the solution [3].

Returning to the question at hand, the SiO_2 liner thickness ($\sim$ 7 nm) is $<<$ Al_2O_3 (500 nm) or SiC n-pillar thickness (700 nm). Hence neither removal of this liner nor relocation of N_I from the Al_2O_3/SiO_2 interface to the SiC surface affect the n-pillar field. Thus, the simulated field distributions in the SiC and Al_2O_3 regions of Fig. 1(b) would be almost the same as those in Fig. 1(a). Hence, the $E_{R,SiO2}$ derived from the SiC region fields using (1) would match the actual $E_{R,SiO2}$ in the CSSJ of Fig. 1(a). The validity of our approximation is further confirmed by the fact that, in Fig. 2(a), over most of the pillar length, the simulated $E_{x,SiC}$ matches the value $qN_I/\varepsilon_{SiC}\varepsilon_0$ where $N_I = 7 \times 10^{12}$ cm^{-2} as predicted by sound analytical theory.

III. CONCLUSION

We have clarified an elegant approximation employed in [1] to numerically simulate the field in the SiO_2 layer of the Charge-Sheet Superjunction overcoming the interface charge placement limitation of the device simulator. Our present approximation was shown to be a case of transfer of an existing approach to new surroundings. Our note reinforces the insight – "Modeling is the art of making approximations."

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