Depletion Width of a Nonuniformly Doped Schottky Barrier Diode

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ABSTRACT

Depletion width of a nonuniformly doped Schottky barrier diode is obtained by solving Poisson's equation. The calculation of depletion width of a nonuniformly doped Schottky barrier diode is rarely treated in the literature. Previous works on Schottky barrier diode considered only uniformly doped doping density. The present analysis is of great importance for the design of Schottky barrier MOSFET where doping density is not uniform.

Keywords: **Schottky barrier diode; nonuniform doping and depletion width of a junction.**

INTRODUCTION

Application of Schottky barrier as Schottky barrier MOSFET is gaining popularity [1]-[2]. As MOS transistors are continuously scaled, parasitic effects begin to diminish performance improvements and can lead to device failures. One proposed solution to the problematics relating to source and drain (S/D) junctions is the introduction of metallic materials in place of conventional doped semiconductor. There are numerous motivations for replacing doping (n^+ or p^+) with metal in the S/D regions, including low parasitic S/D resistance, low-temperature processing for S/D formation, elimination of parasitic bipolar action, which is due to the low resistance of metal [3].

Doping within Si region of such SBMOSFET is not uniform [4]-[6]. No analytical work considering non-uniformly doped Si Schottky barrier diode (SDB has been done till now. In the present work, the depletion layer of a nonuniformly doped SBMOSFET is determined analytically. The expression for depletion layer can be used in studying characteristics of SBMOSFET.

DERIVATIONS

The structure of SBMOSFET is shown in Fig. 1. In conventional PMOSFET source and drain regions are formed by p^+ doping. In SBMOSFET heavily doped source and drain regions are replaced by metal. SBMOSFET with N-substrate performs better than its counter part SBMOSFET with P-substrate. A depletion region will be formed at metal-silicon junction. Fig. 2 shows a planer n-Si Schottky barrier diode for the analysis. The doping profile can be approximated by Gaussian distribution. Gaussian profile is given by

$$N_D(x) = N_o e^{-(ax^2)} \, cm^{-3} \tag{1}$$

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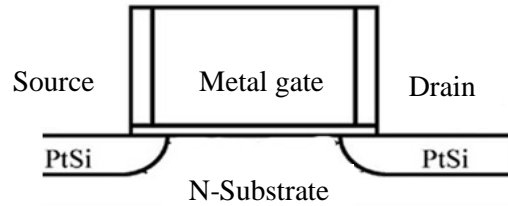Where N_o is peak doping density at x = 0, a is logarithmic slope of the doping profile.

Fig.1. Cross sectional view of a SB-PMOSFET.

In order to simplify the Poisson's equation one approximation is introduced, as follows,

Vanishing electric field at the edge of the depletion region [8]:

It may be justified by noting that the magnitude of the electric field inside the depletion region is much higher compared to the neutral region.
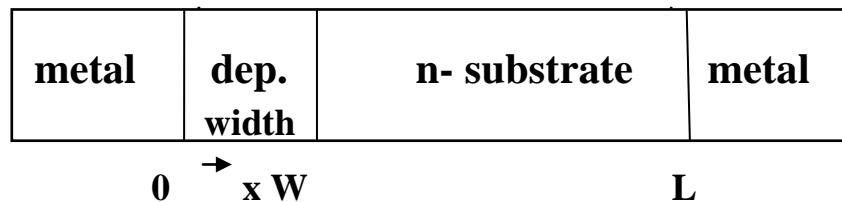

Fig. 2. A planer n-Si Schottky barrier diode with depletion region of width W and total length L.

Poisson's equation within the depletion region

$$\frac{dE}{dx} = \frac{q}{\varepsilon_s} N_0 e^{-ax^2} \tag{2}$$

Integration of eqn. (2) gives

$$E(x) = \left(\frac{q}{\varepsilon_s} N_0\right)\left(\frac{1}{2}\sqrt{\frac{\pi}{a}}\right) \text{erf}(\sqrt{a}x) + C_1 \tag{3}$$

At the edge of the delpetion region i.e. at x = W, E(W) = 0. Using this boundary condition the arbitrary constant C_1 can be evaluated . The electric field E (x) within depletion region can be written as

$$E(x) = -\left(\frac{q}{\varepsilon_s} N_o\right)\left(\frac{1}{2}\sqrt{\frac{\pi}{a}}\right)\left(\text{erf}(\sqrt{a}W) - \text{erf}(\sqrt{a}x)\right) \tag{4}$$

The voltage distribution within the depeletion region can be obtained by integrating E(x)

$$V(x) = -\int E(x)\, dx + C_2$$

$$= \left(\frac{q}{\varepsilon_s} N_o\right)\left(\frac{1}{2}\sqrt{\frac{\pi}{a}}\right)\left[x \, erf(\sqrt{a}\,W) - \frac{1}{\sqrt{a\pi}}\{\sqrt{a\pi}\, x erf(\sqrt{a}x) + exp(-ax^2)\}\right] + C_2 \qquad (5)$$

Using boundary condition at x= 0, V(0) = 0 the arbitrary constant C_2 can be easily evaluated. The voltage V(x) will become

$$V(x) = \left(\frac{q}{\varepsilon_s} N_o\right)\left(\frac{1}{2}\sqrt{\frac{\pi}{a}}\right)\left[x \, erf(\sqrt{a}W) - \left\{x \, erf(\sqrt{a}x) + \frac{1}{\sqrt{a\pi}} exp(-ax^2)\right\} + \frac{1}{\sqrt{\pi a}}\right] \qquad (6)$$

At thermal equilibrium, the built-in voltage across the depletion region is V_{bi} and the depletion width is W = W_o. The built-in voltage V_{bi} can be obtained from eqn. (6)

$$V_{bi} = \frac{1}{2a}\left(\frac{q}{\varepsilon_s} N_o\right)\left(1 - e^{-aW_o^2}\right) \qquad (7)$$

For SBD, V_{bi} is given by [9]

$$V_{bi} = \emptyset_B - \frac{kT}{q}\left(\ln\frac{N_c}{N_D(W_o)}\right) = \emptyset_B - \frac{kT}{q}\ln\frac{N_c}{N_o} - \frac{kT}{q}(aW_o^2) \qquad (8)$$

Where φ_B is the barrier height and W_0 is the width at thermal equilibrium and N_C ($\approx 2.8 \times 10^{19}$ cm^{-3}) is the effective density of states in the conduction band. From eqns. (7) and (8), W_o can be obtained. The doping profile can also approximated by complementary error function instead of Gaussian distribution. For such profile, $N_D(x)$ is given by

$$N_D(x) = = N_o \, erfc(x) = N_o(1 - erf(x)) \qquad (9)$$

Solving Poisson's equation with appropriate boundary conditions, E(x) and V(x) can be obtained as

$$E(x) = -\left(\frac{q}{\varepsilon_s} N_o\right)(W - x) + \left(\frac{q}{\varepsilon_s} N_o\right)(W erf(W) - x erf(x)) + \left(\frac{q}{\varepsilon_s} N_o\right)\left(\frac{1}{\sqrt{\pi}}\right)\left(exp(-W^2) - \frac{1}{\sqrt{\pi}} exp(-x^2)\right) \qquad (10)$$

and

$$V(x) = \left(\frac{q}{\varepsilon_s} N_o\right)\left(Wx - \frac{1}{2}x^2\right) - \left(\frac{q}{\varepsilon_s} N_o\right)\left((Wx) erf(W) - \frac{2}{\sqrt{\pi}}\left(\frac{x^3}{3} - \frac{x^5}{12}\right)\right) - \left(\frac{q}{\varepsilon_s} N_o\right)\left(\frac{1}{\sqrt{\pi}}\right)\left(x exp(-W^2) - \frac{1}{2} erf(x)\right) \qquad (11)$$

In obtaining eqn. (11) erf(x) is approximated by

$$erf(x) = \frac{2}{\sqrt{\pi}}\left(x - \frac{x^3}{3}\right) \qquad \text{for} \quad x << 1$$

RESULTS AND DISCUSSIONS

The electric field E(x) within the depletion region can be obtained from eqn.(4). The electric field distribution within the depletion region of an SDB for a given peak doping density N_o and the length L=1μm is shown in Fig. 3. The peak of E(x) occurs at x = 0 i.e. at the metal-Si junction. For uniformly doped SDB, E(x) varies approximately linearly. For the doping density given by eqn. (1), E(x) does not vary linearly with x.
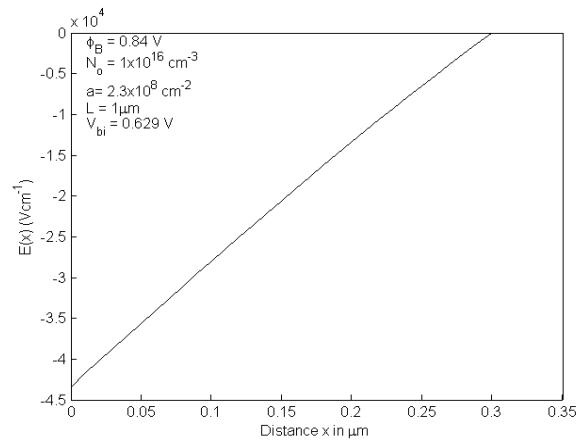
Fig. 3. Electric field distribution within the depletion region.

The voltage V(x) within the depletion region as function of x is shown in Fig. 4. It is zero at the metal-Si junction. It increases with x and becomes maximum at the edge of the depletion region i.e at $x = W_o$.
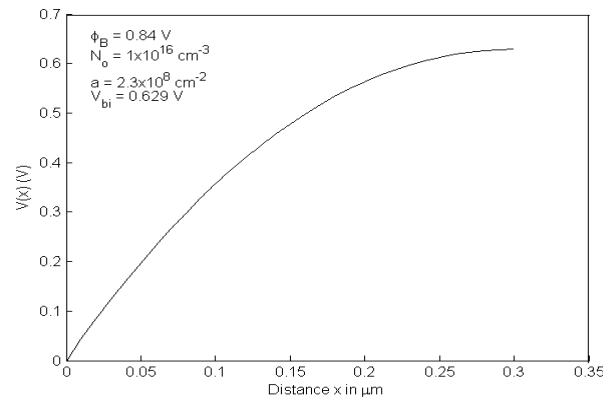
Fig. 4. Voltage within the depletion region of a SBMOSFET.

CONCLUSION

In the work, mathematical expressions for electric field distribution E(x) and voltage distribution V(x) within the depletion region of a Gaussian doped Si substrate of SBMOSFET are obtained. In studying current-voltage characteristics and breakdown voltage of the metal-substrate of SBMOSFET, eqn. (6) can be used. This is the first time a mathematical formulation for voltage within the substrate of a SBMOSFET is obtained. The voltage within depletion region V(x) for complementary error function doping concentration is also obtained.

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