MATHEMATICAL ESTIMATION OF AVALANCHE BREAKDOWN VOLTAGE EQUATION IN VERTICAL DIMOSFET WITH GAUSSIAN DOPING PROFILE ON 4H- SIC WAFER

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ABSTRACT

The present work aims at the mathematical analysis and estimation of avalanche breakdown voltage equation for a Gaussian doping profile in the drift region of Vertical DIMOSFET with 4H- SiC wafer. With the help of ionization integral equation for avalanche breakdown condition, an equation has been derived that will provide values of depletion width needed for avalanche breakdown in this device. With these real depletion width values and selection of device height 'h', function constant 'm' and peak concentration $'N_0'$ *avalanche breakdown voltages can be estimated.*

Keywords- Avalanche breakdown voltage, DIMOSFET, Gaussian profile, Impact ionization coefficient, Silicon, Silicon Carbide

Introduction

Silicon carbide (SiC) is a potential compound semiconductor for high temperature, frequency, and power electronic applications. It is mainly due of its wide energy band gap, high saturated drift velocity, high breakdown electric field and high thermal conductivity. There are different polytyes of SiC with stacking order between the double layers of carbon and silicon atoms define the difference. The most important polytypes are hexagonal 4H, 6H and cubic 3C-SiCform. The distinct polytypes differ in both band gap energies and electronic properties. Thus band gap varies with the polytype from 2.2eV for 3C-SiC over 3.0eV for 6H-SiC to 3.2eV for 4H-SiC. The development of SiC devices has been mainly based on 4H–SiC which compared to other polytypes has a wider band gap, higher mobility and higher breakdown voltage. The electron mobility of 4H- SiC is almost twice or 10 times that of 6H-

SiC in the direction perpendicular to or along the 6H-SiC c-axis. 4H-SiC devices have lower specific on-resistance with respect to other semiconductors such as Si, GaAs and 6H- SiC[1]. But due to different types of defects such as micropipes, etch pits, super dislocations, planer improvements in crystal growth and device fabrication processes are needed before SiC-based devices and circuits can be scaled-up and reliably incorporated into electronic systems. However, a lot of work is being done in reduction of structural defects, deep level defects, point defects, and carrier lifetime improvement of thick epitaxial layers of 4H- SiC [2-4] .For high power application, calculation of breakdown voltage is an important parameter. There is an unprecedented growth in this area and in recent years breakdown voltage in the range of 12kV has been achieved for IGBTs and the value stand near 20kV for PIN diodes [5-6].
A mathematical analysis has been done in this paper to derive equation for avalanche breakdown voltage for Gaussian doping profile in the drift region of DIMOSFET for 4H SiC wafer.

Theory

The fabrication of vertical DIMOSFET structure is normally done by using planar diffusion technology with a gate such as poly silicon. In these devices, poly silicon gate edge works as a common window for the implantation of p-base and n+ - source regions. Figure 1 represents a cross section of a DIMOSFET structure. Difference in the lateral diffusion between the p-base and n+ source region defines the surface channel region [7]. The forward blocking capability is achieved by the p-n junction between the p-base region and low doped n-drift region. During the device operation, a fixed potential to the p-base region is provided by the connection of base to the source metal through a break in the n+ source region. By applying a positive bias to the drain and short-circuiting the gate to the source, the p-base and n-drift region junction becomes reverse-biased thus supporting the drain voltage by the extension of a depletion layer on both sides of the junction [7]. However, the depletion layer extends primarily into the n-drift region due to its lower doping level as compared to p-base region. A conductive path extending between the n+ - source region and the n-drift region is formed by applying positive bias to the gate electrode. The application of a positive drain voltage results in a current flow between drain and source through the n-drift region and conductive channel.

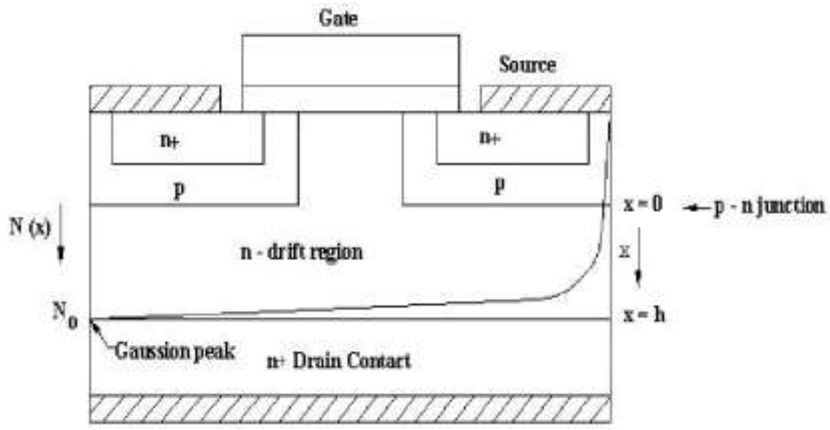

Figure 1.Cross Sectional Structure of DIMOSFET Showing Gaussian Profile in the Drift Region [8]

Doping profiles used in semiconductor industry commercially normally have non-linearly graded profiles inside semiconductor layers. These profiles usually adopt Gaussian, Complementary Error Function distribution or an exponential distribution for improved results [8]. In this paper analysis of Gaussian profile has been adopted with the peak lying at the drain end of the device and the doping concentration falls to small values near the n-drift region and p-base junction. Thus enabling, a low parasitic series resistance near the drain and a large depletion region in the drift region near the junction.

The impact ionization coefficient for a charge carrier is defined as the number of electron–hole pairs created by a charge carrier traversing 1 cm through the depletion layer along the direction of the electric field. Infinite impact ionization rate has been defined as the condition for avalanche breakdown [9]. To analyze this, consider a one-dimensional reverse-biased N^+ P junction with a depletion region extending mainly in the P-region. If an electron–hole pair is generated at a distance *x* from the junction, the electron will move towards the junction to the N^+ -region, while the hole will simultaneously move towards the contact of P-region. These charge carriers under the influence of large electric field in the depletion region will be accelerated until they gain sufficient energy to create electron–hole pairs during collisions with the lattice atoms. Based upon the definitions for the impact ionization coefficients, the hole and the electron will create $[\alpha_n dx]$ and $[\alpha_p\ dx]$ electron–hole pairs when traversing a distance d*x* through the depletion region, respectively. Here, α_n and α_p are the impact ionization coefficients for electrons and holes respectively. Due to a single electron–hole pair initially generated at a distance x from the junction, the total number of electron–hole pairs created in the depletion region is given by [9]

$$M(x) = 1+ \int_0^x \alpha_n M(x)dx + \int_x^W \alpha_p M(x)\, dx \quad (1)$$

where ,W is the width of depletion region. A solution for this equation is given by [9]

$$M(x) = M(0) \exp \left[\int_0^x (\alpha_n - \alpha_p)\, dx\right] \quad (2)$$

Where M (0) represents the total number of electron–hole pairs at the edge of the depletion region. Putting this expression in (1) with $x = 0$ provides a solution for M (0) [9]

$$M(0) = \left\{1 - \int_0^W \alpha_p \exp\left[\int_0^x (\alpha_n - \alpha_p)\, dx\right] dx\right\}^{-1} \quad (3)$$

By putting above expression in equation (1), we have [9]

$$M(x)= \frac{\exp\left[\int_0^x (\alpha_n - \alpha_p)\, dx\right]}{1- \int_0^W \alpha_p \exp\left[\int_0^x (\alpha_n - \alpha_p)\, dx\right] dx} \quad (4)$$

If the electric field distribution along the impact ionization path is known, then above expression for $M(x)$, which is known as the multiplication coefficient results in calculation of the total number of electron–holes pairs created as a result of the generation of a single electron–hole pair at a distance x from the junction. For avalanche breakdown condition, M should be equal to infinity. This condition is obtained by putting the denominator of equation (4) equal to zero [9]

$$\int_0^W \alpha_p \exp\left[\int_0^x (\alpha_n - \alpha_p)\, dx\right] dx = 1 \quad (5)$$

Left-hand side expression is known as the ionization integral. For the analysis of avalanche breakdown in power devices, a voltage at which the ionization integral becomes equal to unity is found out. If the impact ionization coefficients for electrons and holes are supposed to be equal, the avalanche breakdown condition reduces to [9]

$$\int_0^W \alpha\, dx = 1 \quad (6)$$

Equation (6) has been used in the present work for the estimation of avalanche breakdown voltage. This method of determination of the breakdown voltage is valid for power rectifiers and MOSFETs where the current flowing through the depletion region is not amplified [9].

Result and Calculations

Baliga's power law approximation for the impact ionization coefficients for 4H-SiC for analytical derivations is given as [9]

$\alpha = 3.9 \times 10^{-42} E^7$ (7)

where, E is the electric field distribution.

The equation for Gaussian profile is written as [7]

G(x) $= N_0\, exp^{-\left(\frac{h-x}{m}\right)^2}$ (8)

N_0 is the maximum concentration at the drain end, 'h' is device height, m is a function constant. The depletion region width at any given reverse voltage V can be obtained by solving the Poisson's equation for the system.

For the Gaussian function G(x), the Poisson's equation becomes [7]

$- \partial^2 V/\partial^2 x = \left(\frac{eN_0}{\varepsilon_s}\right)\; exp^{-\left(\frac{h-x}{m}\right)^2}$ (9)

ε_s is the relative permittivity of medium and e is the charge of an electron.

Integrating equation (9) from 0 to x will give electric field E as [7]

$E = \frac{-\sqrt{\pi}\, e\, N_0\, m}{2\, \varepsilon_s}\; erf\, \frac{h-x}{m} + C$ (10)

At x=h, E=0 therefore C=0. So, equation becomes [7]

$E = \frac{-\sqrt{\pi}\, e\, N_0\, m}{2\, \varepsilon_s}\; erf\, \frac{h-x}{m}$ (11)

Integrating the above equation for voltage V with proper initial conditions and first order error function approximation, we get [7]

$\frac{W^4}{12\, m^2} - \frac{h\, W^3}{3\, m^2} - \frac{W^2}{2}(1- \frac{h^2}{m^2}) - \frac{\varepsilon_s V}{e\, N_0} = 0$ (12)

Above equation will be used to estimate avalanche breakdown voltage V_a (by replacing V) at a particular depletion width 'W'.

Putting equations (7) and (11) in equation (6), we have

$\int_0^W 3.9 \times 10^{-42} \left[\frac{-\sqrt{\pi}\, e\, N_0\, m}{2\, \varepsilon_s}\; erf \left(\frac{h-x}{m}\right)\right]^7 dx = 1$ (13)

$3.9 \times 10^{-42} \left(\frac{-\sqrt{\pi}\, e\, N_0\, m}{2\, \varepsilon_s}\right)^7 \int_0^W erf\left(\frac{h-x}{m}\right)^7 dx = 1$ (14)

For $\left(\frac{h-x}{m}\right) < 1$, error function can be expressed as:

$erf\left(\frac{h-x}{m}\right) = [\frac{2}{\sqrt{\pi}}\left(\frac{h-x}{m}\right) - \frac{2}{3\sqrt{\pi}}\left(\frac{h-x}{m}\right)^3 + \frac{1}{5\sqrt{\pi}}\left(\frac{h-x}{m}\right)^5 - \frac{1}{21\sqrt{\pi}}\left(\frac{h-x}{m}\right)^7 + \frac{1}{108\sqrt{\pi}}\left(\frac{h-x}{m}\right)^9 + \ldots\ldots]$

Substituting above expression in equation (14) and retaining the first five terms

$3.9 \times 10^{-42} \left(\frac{-\sqrt{\pi}\, e\, N_0\, m}{2\, \varepsilon_s}\right)^7 \int_0^W [\frac{2}{\sqrt{\pi}}\left(\frac{h-x}{m}\right) - \frac{2}{3\sqrt{\pi}}\left(\frac{h-x}{m}\right)^3 + \frac{1}{5\sqrt{\pi}}\left(\frac{h-x}{m}\right)^5 - \frac{1}{21\sqrt{\pi}}\left(\frac{h-x}{m}\right)^7 + \frac{1}{108\sqrt{\pi}}\left(\frac{h-x}{m}\right)^9]^7\; dx = 1$

(15)

Solving above equation and retaining first two terms in integration, we have

$$3.9 \times 10^{-42} \left(\frac{-\sqrt{\pi}\ \mathrm{e}\ N_0\ \mathrm{m}}{2\ \varepsilon_s}\right)^7 \int_0^W \left[\frac{128}{\pi^{7/2}} \left(\frac{h-x}{m}\right)^7 - \frac{896}{3\pi^{7/2}} \left(\frac{h-x}{m}\right)^9\right] \mathrm{dx} = 1 \quad (16)$$

Solving above equation, we have

$$3.9 \times 10^{-42} \left(\frac{-\sqrt{\pi}\ \mathrm{e}\ N_0\ \mathrm{m}}{2\ \varepsilon_s}\right)^7 \left[\frac{128(-7h^9+3h^7m^2)W}{3m^9\pi^{7/2}} - \frac{448(-3h^8+h^6m^2)W^2}{m^9\pi^{7/2}} + \frac{896(-4h^7+h^5m^2)W^3}{m^9\pi^{7/2}} + \frac{224(28h^6-5h^4m^2)W^4}{m^9\pi^{7/2}} + \frac{896(-42h^5+5h^3m^2)W^5}{5m^9\pi^{7/2}} - \frac{448(-14h^4+h^2m^2)W^6}{m^9\pi^{7/2}} + \frac{128(-28h^3+hm^2)W^7}{m^9\pi^{7/2}} - \frac{16(-84h^2+m^2)W^8}{m^9\pi^{7/2}} - \frac{896hW^9}{3(m^9\pi^{7/2})} + \frac{448W^{10}}{15m^9\pi^{7/2}}\right] = 1 \quad (17)$$

Equation (17) will be solved for real values of depletion width W <h. For that depletion width avalanche breakdown condition is applicable. Putting real values of W from equation (17) into equation (12) will provide the estimated avalanche breakdown voltages V_a for a device height 'h', function constant m and peak concentration N_0.

CONCLUSION

Ionization integral condition for avalanche breakdown voltage has been used for the derivation of a mathematical equation for a Vertical Double implanted Metal oxide field effect transistor with Gaussian doping profile in the drift region for 4H- SiC wafer. Equation (17) will be solved for getting real values of depletion width less than the device height (W<h). These real values of depletion region width can be put into equation (12) for the estimation of avalanche breakdown voltages V_a for a device height 'h', function constant 'm' and peak concentration N_0.

REFERENCES

[1]. R. Talwaar, and A.K. Chatterjee , Estimation of Power Dissipation of a 4H-SiC Schottky Barrier Diode with a Linearly Graded doping profile in the drift region, *Maejo Int. J. Sci. Technol., 3(03*), 2009, 352-365.

[2]. M. Yazdanfar, I. Gueorguiev Ivanov, H. Pedersen, O. Kordina and E. Janzén, Reduction of structural defects in thick 4H-SiC epitaxial layers grown on 4° off-axis Substrates, *Journal of Applied Physics, 113, 223502*, 2013, 1-8.

[3]. J. Renxu, Z. Yuming, and Z. Yimen, Reduction of Deep Level Defects in Unintentionally Doped 4H-SiC Homo-epilayers by Ion Implantation, *Journal of Wuhan University of Technology- Mater. Sci. Ed., 27(3)*, 2012, 415-417.

[4]. T. Miyazawa, and H. Tsuchida, Point defect reduction and carrier lifetime improvement of Si- and C-face 4H-SiC epilayers, *Journal of applied physics, 113, 083714*, 2013, 1-6.

[5]. S. H. Ryu, C.Capell , C.Jonas , L. Cheng, M. O'Loughlin , A. Burk , A . Agarwal, J. Palmour , and A. Hefner , Ultra high voltage (>12 kV), high performance 4H-SiC IGBTs, *24th international symposium on power semiconductor devices and ICS*, 2012, 257 – 260.

[6]. H. Niwa, Feng, Gan, J. Suda, and T. Kimoto , Breakdown characteristics of 12–20 kV-class 4H-SiC PiN diodes with improved junction termination structures, *24th international symposium on power semiconductor devices and ICS*, 2012, 381 – 384.

[7]. M. Vashishath, and A. K. Chatterjee, Theoretical analysis and Design of double implanted MOSFET on 6H silicon carbide wafer for low power dissipation and large breakdown voltage, *Mj. Int. J. Sci. Tech., , 2 (02)*, 2008, 308-319.

[8]. M. Vashishath , *Analysis and design of robust power double implanted MOSFET on 6H Silicon Carbide wafers*, Doctoral diss., Thapar University, Patiala, India, 2008, 96-99

[9]. B. Jayant Baliga, 2008, Fundamentals of power semiconductor devices, Springer, 92-95.