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Simulation Based Analysis of Temperature Effect on Breakdown Voltage of Ion Implanted Co/*n*-Si Schottky Diode

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In semiconductor devices, breakdown voltage variation with temperature is a very significant study, since the reliability and performance of semiconductor devices especially depends upon the temperature. In this paper, the influence of temperature on breakdown characteristic of Ion Implanted edge terminated Co/n-Si Schottky Diode formed on n-Si epitaxial layer has been investigated by using SILVACO TCAD. It is also reported that not only resistive area present in close proximity to the edges of boron ion implanted Schottky diode are responsible for improvement in breakdown voltage but also the formation of PN junction near the edges, affect the breakdown voltage to a significant amount. The dopant concentration of epitaxial layer is $1 \times 10^{15}/\mathrm{cm}^3$. The variation in reverse breakdown characteristics as a junction of temperature in the range of 300-1000 K is presented in this paper. A comparative study of breakdown voltages of Ion Implanted and as-prepared Schottky diode is also presented.

Keyword: Schottky diode, Breakdown voltage, Ion implantation.

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1. INTRODUCTION

Schottky diode is nothing but a metal semiconductor contacts and have potential advantageous applications in modern semiconductor era. Since, Schottky diode is a majority carrier device, a number of literatures have been reported in regard to its applications. This diode is ideal for microwave applications such as mixers and detectors, in FETs, IMPATT diodes, various gating circuits, clamping, nitride oxide gas detection, hazards environment etc. [1-3]. Though, Schottky diodes have a lot of fruitful applications, there is a device limiting phenomenon called edge effect induced breakdown in these devices, which inhibit their frequently usage [4, 5]. In light of this, a lot of work has been done to improve edge effects like moat etch, mesa etching, field plate, guard rings etc. [6-8]. Recently, researchers report high dose implantation with boron ion as a technique to improve the breakdown voltage. This improvement is attributed to formation of resistive region at the edges, whereby edge effect in device is reduced [9, 10]. But, there is still a need for extensive study of this implantation induced effect because boron are group III elements and they would also shows there effect in addition of forming of resistive layer. We have addressed this by TCAD simulations. The results demonstrate the improvement of breakdown voltage due to reduction in edge effect in ion implanted Schottky devices. In addition to this, the breakdown characteristics of as-prepared and ion implanted Schottky diode as a junction of temperature have been also reported.

Schottky Diode is often used in the form of rectangular metallization in some semiconductor devices such as MESFETs. A cross-sectional view of metal semiconductor junction in 2D is shown in Fig. 1.

Value of electric field in the depletion region can be found by solving Poisson equation for total charge in depletion layer as follows:

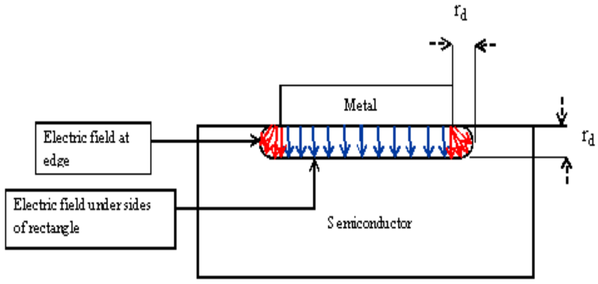

Fig. 1 – Rectangular metallization and electric field crowding at edges

$$\nabla^2 V(r) = -\frac{\rho}{\in} \tag{1}$$

In terms of cylindrical coordinates, equation (1) can be written as

$$\frac{1}{r}\frac{d}{dr}\left[rE(r)\right] = \frac{\rho(r)}{\in} \tag{2}$$

And in terms of spherical coordinates, equation (1) can be written as

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2 E(r)\right] = \frac{\rho(r)}{\in} \tag{3}$$

Where ρ is the charge density in depletion region and $\in$ is the permittivity. Integrating (2) and (3) with boundary condition that electric fields at the boundary of depletion region is zero, will give the electric field as for cylindrical junction

$$E_C(r) = \frac{qN_d}{2\in}\left(\frac{r_j^2 - r_d^2}{r_j}\right) \tag{4}$$

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And for spherical junction

$$E_S(r) = \frac{qN_d}{2\in}\left(\frac{r_j^3 - r_d^3}{r_j^2}\right) \qquad (5)$$

Where r_j is the radius of junction and r_d is the radius of depletion layer. Clearly, we can see that as the radius of junction at the edges decreases, i.e. the edges of the rectangular metallization become sharper, an enhancement of the electric field occurs, which causes early breakdown [11, 12]. So, the main aim of researchers is to minimize this electric field crowding at the edges of the device to improve the reverse breakdown.

2. SIMULATION OF DEVICE

In TCAD Simulation tool, ATHENA performs the device processing steps, and ATLAS performs the electrical characterization like IV, CV and breakdown voltage etc. of the device which enables us to perform virtual wafer fabrication and multi-device characterizations there by eliminating iterations of costly experiments [13]. It is a very efficient tool to see the process effect on electrical characteristics of semiconductor devices. To get the approximate value of any parameter, the appropriate dimensions and meshing parameters suitable for the experiment has been chosen. Initially silicon wafer with 20 μm epitaxial layer on the top of the surface, with low doping (1×10^{15}/cm^3) has been considered. Cobalt metal has been deposited on the surface of wafer to make the Schottky contact. Aluminium was deposited on the back side of the wafer for making Ohmic contact. Since meshing at the interface is very crucial, we have made very fine meshing at interface as compared to other area of the device.

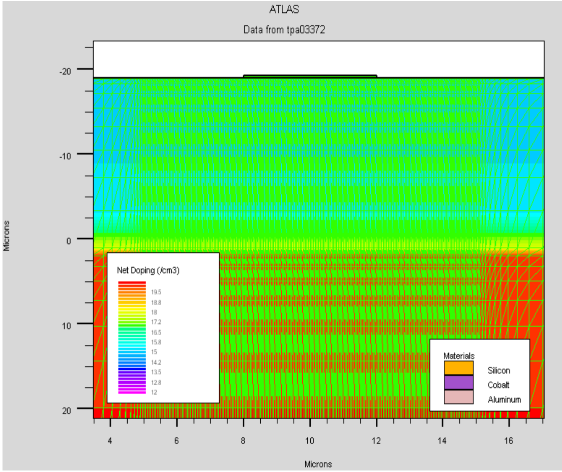

Fig. 2 – Meshing, doping and metallization in simulated device structure

Various models like Shockley-Read-Hall recombination, Conductivity dependent mobility, Band Gap Narrowing and Selberherr Model for Impact ionization etc, have been used to determine the breakdown value of device. Electric field will be high at the edge due to the sharp corners which is shown in Fig. 3. With increasing of this electric field, there will be high current density at the edge as shown in Fig. 4.

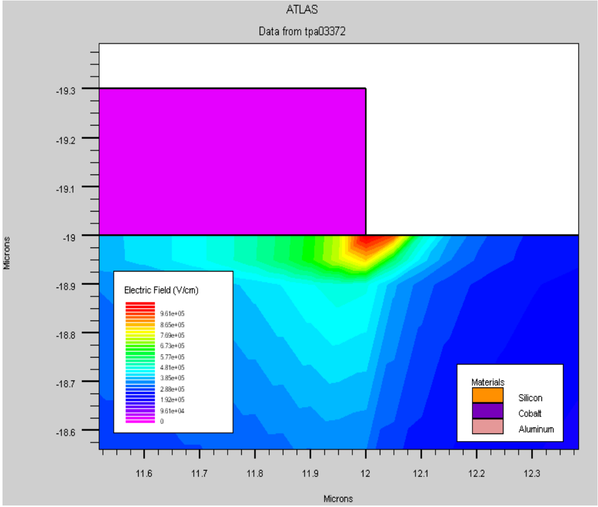

Fig. 3 – Electric field contours reaching peak at the sharp corners or edges

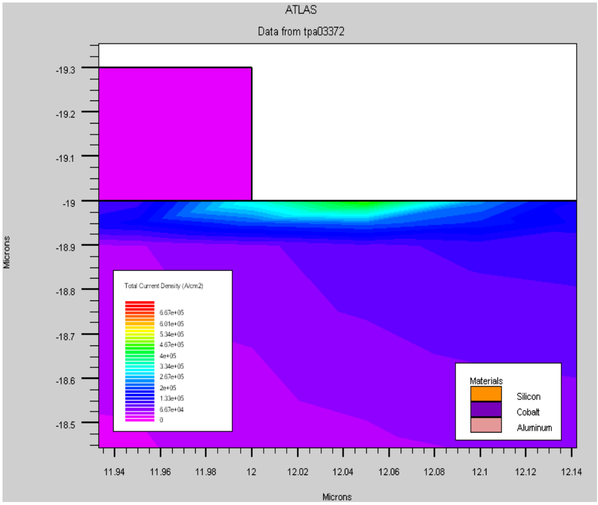

Fig. 4 – Current density at the edges in as-prepared diode

After simulating the as prepared diode, we have implanted the diode with Boron ions at energy 30 keV with a dose of 1×10^{13}/cm^2. In Boron ion implantation, there will be diffusion of impurities laterally which can be seen in Fig. 5.

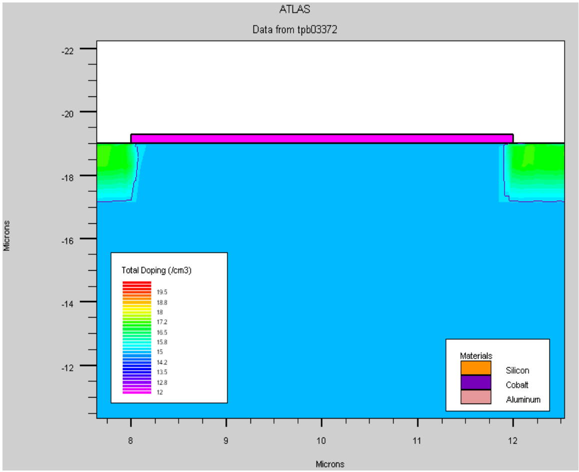

Fig. 5 – Lateral diffusion of impurities

After implantation with boron ions, we see that there is a decrease in current density at the edges due to formation of p-n junction as shown in Fig. 6.

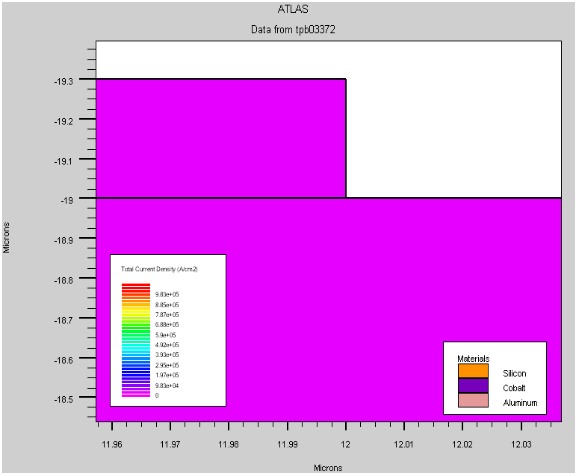

Fig. 6 – Decrease in current density at the edges in implanted diodes in comparison with Fig. 3

3. RESULTS AND DISCUSSION

After carefully examine the above results, we observe that there is high electric field at the edges in case of as-prepared diodes (as shown in Fig. 3, due to which the current density at the edges is high. With this current density, there will be more charge carriers which contribute to impact ionization phenomena and a stage will reach where breakdown will occur and current increase abruptly. In our device it occurs near about 274 Volt. We can see in Fig. 7 that, with variation in temperature from 300-1000 K, up to 600 K, there was an increase in the breakdown value with decrease in leakage current and then from 700-1000 K, there was a decrease in breakdown value with increase in leakage in device.

With these results we can say that simulated device is following the same pattern as given in the literature [14-16]. As we go up to 600 K, there was an increase in breakdown voltage due to scattering of charge carriers with interaction to host atoms phonons, causes decrease in their mean free path, and thus charge carriers are not capable of gaining sufficient energy to induce the breakdown at this stage. To induce breakdown in device, they should acquire more energy from applied field and hence breakdown voltage will increase.

A general formula for decrease in mean free path with increase in temperature is given as [14]

$$\lambda = \lambda_0 \tanh\left(\frac{E_p}{2kT}\right) \qquad (6)$$

We can see in equation (6) that there is an inverse relationship between temperature and mean free path due to which mean free path will decrease with rise in temperature i.e. up to 600 K. With increase in temperature beyond a certain limit i.e. above 600 K, the band gap narrowing phenomena comes into play. Due to this band gap narrowing phenomena, more carriers can easily tunnel through the band, as less energy is required to cross the band here and hence there will be decrease in breakdown voltage at high temperatures.

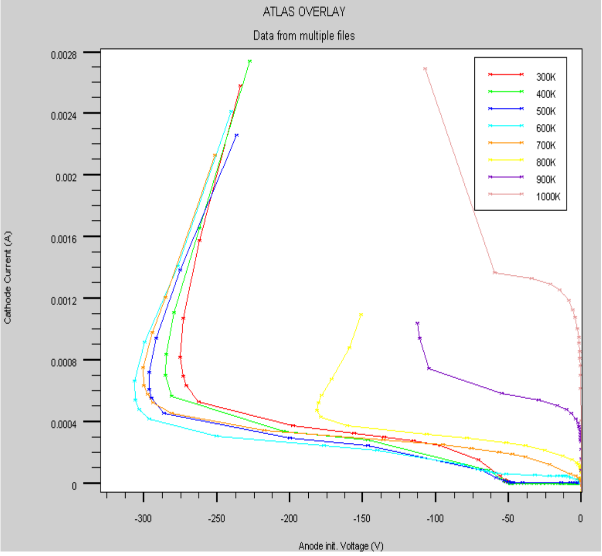

Fig. 7 – Breakdown voltage variation with temperature for as prepared diodes

To increase the breakdown voltage, we implant diode with boron ions. These are group III elements, which makes PN junction at the edges. This junction formation at edges and laterally diffusion of impurity atoms, causes lowering of potential as well as current density which can be seen in Fig. 6. Due to this there will be decrease in electric field at edges and hence increase in breakdown voltage. We have also implant diode with ions other than group III ions, which show no significant improvement in breakdown voltage diode, which clearly shows that PN junction at edges and laterally diffusion of impurities is the main reason behind this improvement. A systematic plot of breakdown voltage vs temperature is shown in Fig. 8.

From Fig. 8, we can see that, as we increase the temperature, from 300-600 K, there is increase in breakdown voltage from 350 V to 418 V and decrease in leakage current, after reaching at maximum, further increase in temperature, from 700-1000 K, there is decrease in breakdown voltage. With these results, we

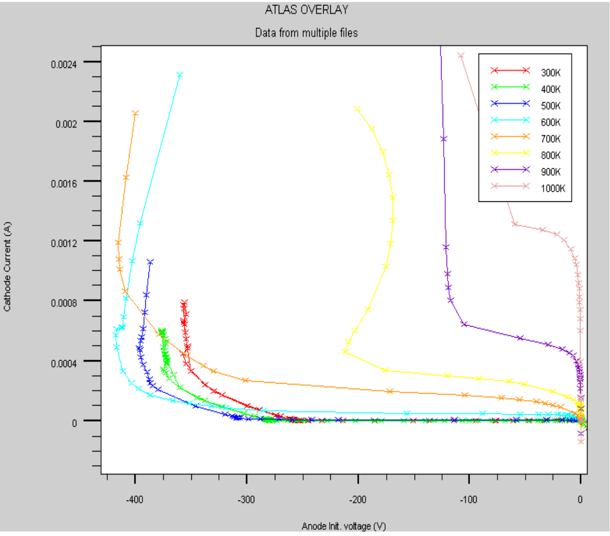

Fig. 8 – Enhancement of BD Voltage with boron ion implantation and BD Voltage variation with temperature

can say that, implanted diode follows the same pattern as as-prepared diode due to same reasons discussed above. A detailed study related to leakage current in ion implanted and as-prepared diode is under discussion. A comparative study of variation in breakdown voltage with temperature in as-prepared and ion implanted can be seen in Table 1 as below

Table 1 – Variation of Breakdown with temperature in as-prepared and implanted diode

Serial No.	Temperature (K)	As Prepared diode (V)	Implanted Diode (V)
1	300	275	350
2	400	283	372
3	500	293	388
4	600	306	418
5	700	300	416
6	800	180	210
7	900	112	120
8	1000	60	60

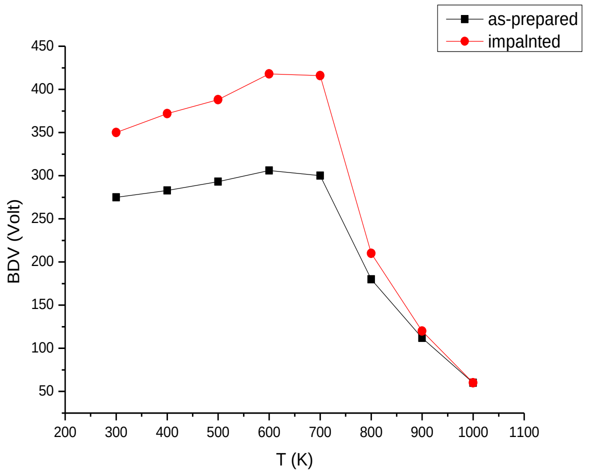

Fig. 9 – Break down voltage variation with temperature in as-prepared and implanted diodes

As seen from graph (Fig. 9), implanted diode shows increment in breakdown voltage. This kind of behaviour could be attributed to the lateral diffusion of impurity atoms at edges and formation of PN junction there. This formation of PN junction is responsible for potential lowering as well as decrease in current density at the edges. Temperature related study set a limit up to which silicon based Schottky diodes can operate.

4. CONCLUSION

Variation of breakdown characteristics of ion implanted Schottky diodes with temperature has been investigated using SILVACO TCAD. It has been found that, blanket way boron implantation as an edge termination method, improves the breakdown voltage of the Schottky diode. The PN junction formation and lateral diffusion of group III impurities hamper the electric field crowding at the edges, which is the reason behind the increment in breakdown voltage. The breakdown voltage variation with temperature up to 600 K is due to variation in mean free path of carriers (λ). At higher temperature (700-1000 K), band gap narrowing phenomena comes into play due to which breakdown voltage will decrease.

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