SiC Pressure Sensors Radiation Hardness Investigations

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Abstract

Radiation investigations of SiC-based pressure sensors were carried out. It was experimentally shown that these devices are more thermal stable and radiation hard as compared to the Si-based pressure sensors. It is connected with the basic physical properties of SiC such as wide bandgap, high thermal conductivity etc. The theoretical investigations were performed to explain the experimentally measured radiation hardness of SiC pressure bridge under dose rate, total dose and neutron flux irradiation. The good agreement between theoretical and experimental data confirms the high potential of SiC devices for harsh applications

I. INTRODUCTION

Silicon Carbide (SiC) is an advanced material for harsh applications [1]. SiC-based resistive bridge circuits are widely used as pressure sensor components [2] in space, experimental physics, and other applications with radiation hardness requirements. It was experimentally shown that these devices are more thermal stable and radiation hard as compared to the Si-based pressure sensors. The measured SiC bridge disbalance voltage residual deviations from the initial values did not exceed 2% after the dose rate $5\cdot10^{10}$ rad(Si)/s, total dose 10^6 rad(Si)/s and neutron flux 10^{13} n/cm^2 irradiation. The voltage shift after all influences did not exceed 22% of the initial value in -60...+125^{o}C temperature range [3].

The theoretical investigation of SiC sensors radiation behavior was performed using "DIODE-2D" simulator [4]. The "DIODE-2D" is the two-dimensional solver of the fundamental system of equations. The approximation of current density in convection-diffusion equations stable at high mesh Reynolds numbers is applied and algorithm of fast numerical assembly of Jacobean for two-dimensional problems is used. "DIODE-2D" takes into account carrier generation, recombination and transport, optical effects, carrier's lifetime and mobility dependencies on excess carriers and doping impurity concentrations. All of parameters are temperature dependent. The simulator was modified to correspond the physical and electrical properties of 6H-SiC.

II. DEVICE UNDER TEST DESCRIPTION

The devices under test were pressure sensors based on 6H SiC strain-resistors in a bridge circuit (Fig.1a). Device cross-section is presented in Fig.1b.

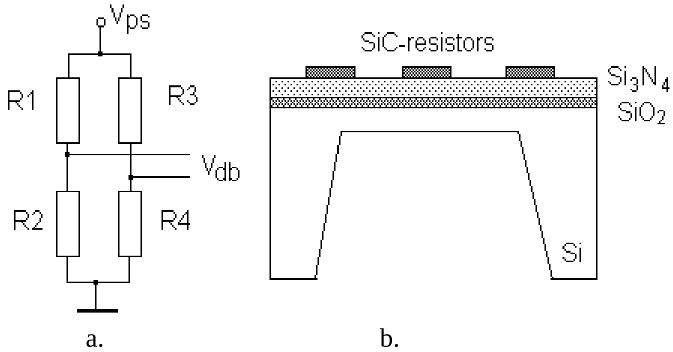


Figure 1: SiC-based pressure sensor circuit (a) and cross-section (b)

All four SiC resistors are placed on the shared Si-substrate (n-type, spread resistance 4.5 kΩ/□) which has been encroached from the bottom up to make a 20...30 μm membrane. The membrane total area is 1,2×1,2 mm^2 while dimension of each resistor is 50×100 μm^2. The upper surface of Si-membrane is covered with two insulator layers: SiO_2 (0.3 μm) and Si_3N_4 (1 μm). Therefore the introduced pressure sensor is SiC-On-Insulator (SCOI) device which is similar to well known SOI structures but with SiC instead of Si [5]. Ti/Ni metallization was used. The devices were manufactured by ETU Center of Microtechnology and Diagnostics (Russia) [6].

III. SIC RADIATION BEHAVIOUR MODELING

The special set of physical parameters was introduced into "DIODE-2D" simulator for the purpose of adequate SiC devices modeling. The electrical properties of 6H-SiC such as electron and hole mobility doping and field dependencies, band gap temperature dependency, etc. were taken in accordance with DESSIS-ISE simulator [7]. The initial minority carrier lifetimes in 6H-SiC were taken 20 ns. The radiation hardness parameters were estimated to take into account the dose rate and neutron displacement effects.

The dose rate response of resistive bridge circuit is determined mainly by radiation-induced conductivity modulation in resistors. Free carrier generation rate in a semiconductor material can be estimated as follows:

$$G(P_\gamma) = 10^{16}\cdot\rho_o\cdot P_\gamma/(1.602\cdot E_i) = g_0\cdot P_\gamma, \qquad (1)$$

where P_γ is gamma pulse dose rate in rad/s, ρ_o is the semiconductor density in cm^{-3} and E_i is the ionization energy (E_i = 2.67 E_g + 0.86 in eV, E_g is band gap energy).

The difference between Si and SiC structures dose rate responses corresponds at least to their ρ_o and E_i values differences, that results in individual g_o values. Taking into account E_{gSiC} = 3.02 eV and ρ_{oSiC} = 3.2 g·cm^{-2}: one will have g_{0SiC} = 2.24·10^{13} pairs·cm^{-3}·rad^{-1} as compared to well known g_{0Si} = 4.33·10^{13} pairs·cm^{-3}·rad^{-1}. Thus the conductivity modulation in SiC resistors is at least twice (4.33/2.24 ≈ 2) less as compared to the equivalent Si resistors.

To provide the possibility of laser dose rate simulation modeling the optical parameters of 6H-SiC were used in “DIODE-2D” software. The optical absorption coefficient data were taken from [8]. In accordance with this paper the 6H-SiC optical absorption coefficient dependence in the range from 3 to 4.1 eV may be estimated as follows:

$$\alpha = 3400(h\nu - E_g)^2, \quad (2)$$

where α is absorption coefficient in cm^{-1}, $h\nu$ is photon energy in eV.

It’s necessary to take into account that optical band gap from (2) may differ from electrical one used in (1). The best agreement with optical experimental results provides E_g = 2.97 eV in (2).

The displacement effects caused by neutron radiation influence the carriers concentrations, mobilities and lifetimes. As shown in [9] the neutron irradiation of 6H-SiC (with doping level near 10^{17} cm^{-3}) provides the deep acceptor level. The relatively high value of mean displacement threshold energy (near 21.8 eV) ensures the SiC devices additional advantage before Si. The estimated initial carriers removal rate was defined as approximately 3.5 cm^{-1} at room temperature. This value at least 4..5 times less as compared to equivalent Si.

The neutron flux carriers mobility dependence was expressed as

$$\mu_F = \mu_{\cdot 0}/(1 + B_0\mu_{\cdot 0}F_N), \quad (3)$$

where $\mu_{\cdot 0}$ and μ_F are initial and neutron flux damaged mobilities, F_N is neutron flux in cm^{-2} and B_0 is carriers mobility dependence parameter.

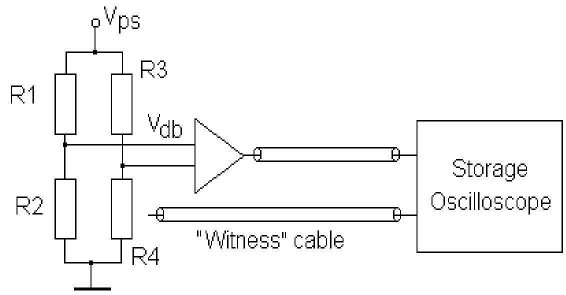
In accordance with experimental data $B_0 \cong 10^{-16}/\mu_0$ for 6H-SiC. This value has a good advantage before Si. However it is necessary to note that initial mobilities in Si at least three times larger than that in SiC.

The neutron flux carriers lifetimes dependencies are strongly dependent of manufacture technology. However the parameters of resistive sensor are slightly dependent of carriers lifetimes and initial lifetimes in SiC are very low to be strongly influenced by moderate neutron fluxes.

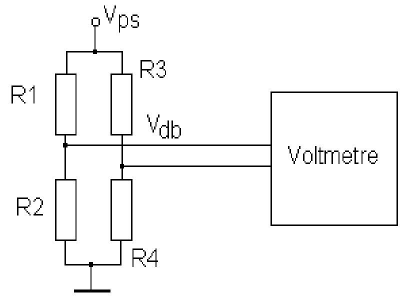
The “DIODE-2D” simulator was modified to take into account these SiC radiation dependencies.

IV. TEST TECHNIQUE DESCRIPTION

The test technique is aimed to measure radiation induced bridge disbalance voltage shift under and after radiation influence. The experimental diagram is presented in Fig.2.



a.



b.

Figure 2: The experimental diagram for transient (a) and static (b) measurements

One common lead of the resistive bridge was connected to the power supply and the other was grounded. As a rule the power supply voltage was in the range 3 to 5 V but in some tests it was rised up to 30 V.

In transient (dose rate) measurements voltage disbalance signal through the interface unit was connected to one of the differential inputs of the storage oscilloscope. The “witness” cable is connected to the other input in order to exclude parasitic electromagnetic flashes.

The following test installation (RISI) were used as radiation sources: flash X-ray (gamma) machine with pulse duration 21.5 ns and maximum dose rate 5.1·10^{10} rad(Si)/s; Co-60 source with dose rate 200 rad(Si)/s and pulse nuclear reactor.

Under and after each radiation influence the bridge disbalance voltage shift was measured in laboratory conditions. And after all radiation influences the parameters values were measured within the -60...+125 ^{o}C temperature range.

The measurements within high and low temperature ranges were provided by the conventional climatic test installation.

V. NUMERICAL TO EXPERIMENTAL COMPARATIVE RESULTS

The radiation induced bridge disbalance voltage transient shift amplitude was found direct proportional against gamma pulse dose rate, as shown in Fig .3.

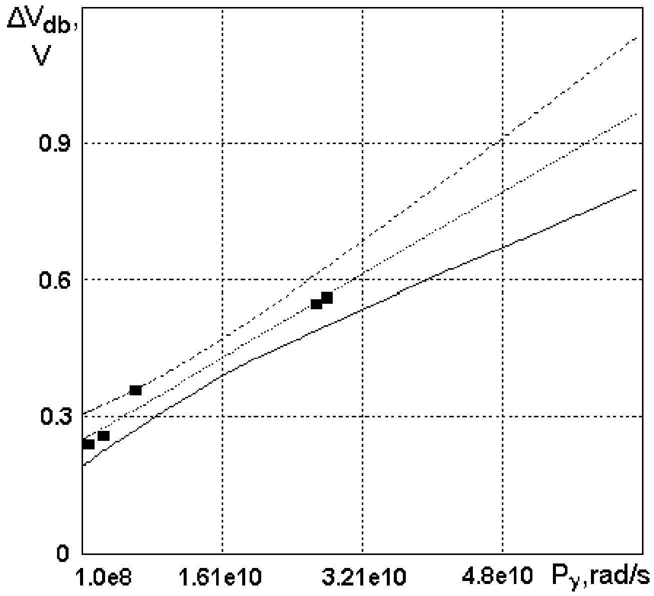


Figure 3: The typical measured disbalance voltage transient shift amplitude vs. dose rate dependence (within 0.95 confidence range borders).

The typical dependence (for Sample #5) can be described with the following direct line approximation:

$$\Delta V_{db}\,(P_\gamma) \approx 0.3 + 7.5 \cdot 10^{-12} \cdot P_\gamma \text{ [V]}$$

where P_γ is dose rate in rad(Si)/s.

It is interesting to note, that the sign of output voltage deviation was identical for all of samples. The voltage transient shift duration under gamma pulse at $2 \cdot 10^{10}$ rad(Si)/s for all sensors did not exceed 100 ns.

However the numerical simulation of sensor dose rate behavior did not predict these results. The calculated disbalance voltage transient shift connected with SiC resistor modulation did not exceed several millivolts (less than 2,5 mV under 22 ns gamma pulse up to $2 \cdot 10^{10}$ rad(Si)/s). The sign of disbalance voltage depends on initial bridge resistor technology difference and must differ from sample to sample.

To explain with mismatch the detailed investigation of pressure sensor circuit was performed. Fig. 4 shows the plane view of sensor including resistive SiC layers and metallization. One can see that resistive structure of sensor is symmetrical and SiC dose rate modulation cannot explain the experimental results.

It was supposed that the observed disbalance is connected with sensor dielectric layers conductivity modulation. The equivalent circuit for dose rate behavior calculation in this case is presented in Fig. 5. The RVi resistors represent the appropriate dielectric layers conductivity under dose rate. Large area and asymmetrical form of metallization can cause the sufficient mismath during irradiation.

The numerical results taking into account the dielectric layers conductivity modulation were obtained and they are in a good agreement with the experimental values. The calculated disbalance consists 0.4 V at dose rate 10^{10} rad(Si)/s that corresponds the experimental transient shift (see Fig. 3).

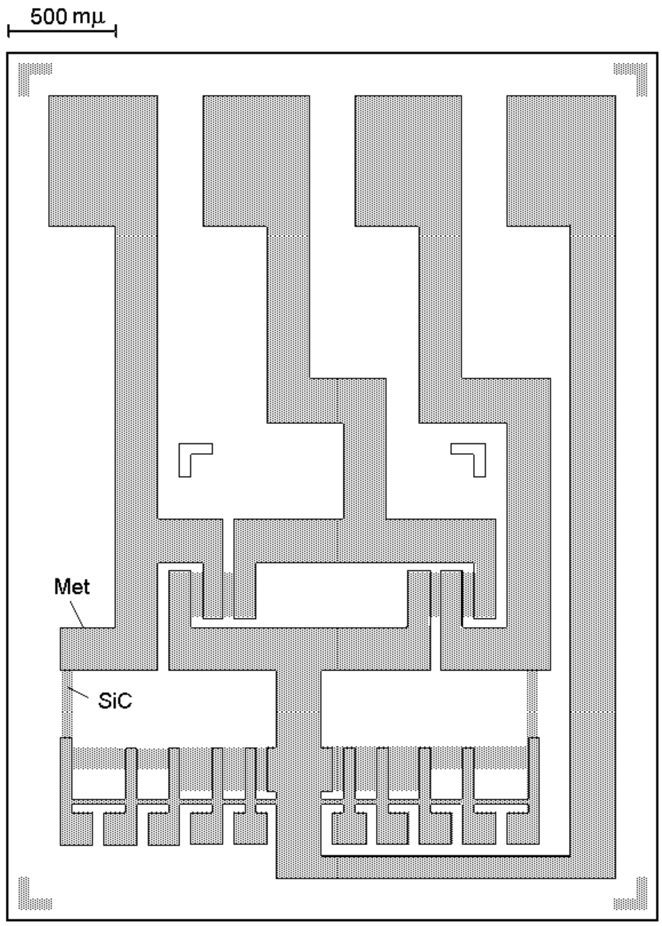


Figure 4: The plane view of SiC-based pressure sensor

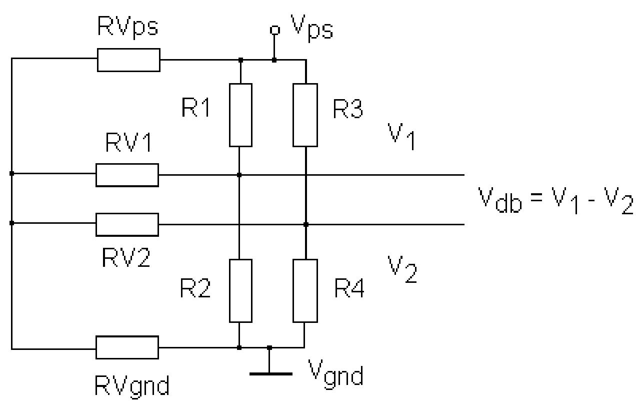


Figure 5: The equivalent circuit for dose rate behavior calculation with the account of dielectric layers conductivity modulation

The voltage shift after a steady state Co-60 irradiation with total dose 10^6 rad(Si) did not exceed 2% of the initial value for all but two devices. In samples # 5 and 6 the disbalance voltage reduced essentially (in about 2 times) and its sign even changed the polarity in sample #5. This results are mainly due to the total dose degradation of the protective lacquer but not of SiC-resistors.

The additional neutron flux of 10^{13} n/cm^2 caused the negligible disbalance voltage variation in sensor samples. The measured SiC bridge disbalance voltage residual deviations from the initial values did not exceed 2%. Similar results were obtained with the help of numerical simulation using initial carriers removal rate 3.5 cm^{-1}.

VI. CONCLUSION

Radiation investigations of SiC-based pressure sensors have shown that these devices are more radiation hard as compared to the Si-based pressure sensors.

The gamma-pulse induced bridge disbalance voltage transient shift amplitude was found direct proportional against gamma pulse dose rate and consists near 0.4 V at dose rate 10^{10} rad(Si)/s. The voltage transient shift duration under gamma pulse at $2 \cdot 10^{10}$ rad(Si)/s for all sensors did not exceed 100 ns. It was found that the observed disbalance cannot be explained by SiC resistors modulation and connected with sensor dielectric layers conductivity modulation.

The measured SiC bridge disbalance voltage residual deviations from the initial values did not exceed 2% after the dose rate $5 \cdot 10^{10}$ rad(Si)/s, total dose 10^6 rad(Si)/s and neutron flux 10^{13} n/cm^2 irradiation.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

1. A.Y.Nikiforov, V.A.Telets, A.V.Afanasjev, V.A.Ilín, A.V.Korljakov, V.V.Luchinin, O.V.Subbotin, M.V.Chetvergov “Radiation Resistance of temperature, pressure and/or ultraviolet sensors based on silicon carbide and aluminum nitride” Abstracts of III International Workshop on Silicon Carbide and related Materials - ISSCRM-2000, May 24-26, 2000, p.129
2. A.V.Korlyakov, S.V.Kostromin, V.V.Luchinin, A.P.Sazanov, “Silicon carbide pressure microsensor”, Trans. Of Third Int. Conf. “High Temperature Electronics Conference”, Albuquerque, NM, USA, 1996, pp.X-29-X-31.
3. A.Y.Nikiforov, V.V.Luchinin, A.A.Korlyakov, V.S.Figurov, “SiCOI Pressure sensor radiation response”, Presented at 5th Europ. Conf. “Radiation and its effects on component and systems”, Fontevraud, France, 1999, 13-17 sept.
4. The "DIODE-2D" Software Simulator Manual Guide, SPELS, 1999.
5. V.V.Luchinin, A.V.Korlyakov, “The silicon carbide-on-insulator structure as a subject of thermal investigations”, Trans. Of 3rd TERMINIC Workshop, Cannes, France, 1997, pp.260-265.
6. B.S.Ballandovich, S.V.Bogachev, V.A.Il’yn, V.A.Korlyakov, “Realization of silicon carbide sensors for measurements on gaseous working fluids”, Materials Science and Engineering. B46, 1997, pp.383-386.
7. ISE TCAD Software Release 4.1. ISA Integrated System Engineering Inc., Mountain View, CA, USA.
8. Choyke W.J., Patric L. Higher Absorption Edges in 6H SiC// Physical Review. – 1968. Vol.172, N3 – P.769 – 773.
9. McLean F.B., McGarrity J.M., Scozzie C.J. et al. Analysis of Neutron Damage in High-Temperature Silicon Carbide JFETs//IEEE Trans. 1994. Vol. NS-41, N 6. - P. 1884 - 1894.