OPERATION OF THE FOXFET STRUCTURE FOR BIASING Si STRIP DETECTORS: A DEVICE MODELING APPROACH

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Abstract: FOXFET structure is used to bias detector structures built on high ohmic substrates. Its basic advantage is device simplicity and high dynamic resistance. However, several design parameters and processing imperfections can influence operation of the device. The work presents analysis of operation of the FOXFET structure using numerical device simulation. The floating strip junction has been modeled by a zero current source applied to the strip junction. The oxide charges, forming accumulation of carriers at the semiconductor/oxide interface significantly influence the strip potential and result in current flow of carriers from the strip to the drain through the bulk, avoiding the accumulation layer. Dynamic resistance of the FOXFET structure has been modeled by numerically differentiating the Vs/Is data, and show decrease of dynamic resistance with increasing strip current, consistent with the measurement results.

Modeliranje delovanja FOXFET strukture za napajanje Si strip detektorjev

Ključne besede: polprevodniki, detektorji sevanja, delci visokoenergijski, detektorji delcev visokoenergijskih, detektorji polprevodniški monokristalni silicijevi, substrati visokouporovni, FOXFET MOSFET strukture poljskooksidne, modeliranje numerično, naprave polprevodniške, naboji v oksidih, upornosti dinamične, določanje točk delovnih, plasti akumulacijske

Povzetek: FOXFET struktura nadomešča uporovni element potreben za priključitev polprevodniškega detektorja radiacije, procesiranega na visoko-ohmskem substratu, na napajanje. Glavna prednost te strukture je enostavna zgradba ter visoka dinamična upornost, pomanjkljivost pa močan vpliv procesnih parametrov in še posebno strukturnih neidealnosti. V tem delu je predstavljena analiza delovanja FOXFET strukture s pomočjo numerične simulacije. Plavajoč spoj strip/substrat (spoj brez priključene napetosti) je modeliran z ničnim tokovnim virom priključenim na strip. Naboj v oksidu povzroči akumulacijo nosilcev na površini spoja polprevodnik/oksid in močno vpliva na potencial stripa ter povzroči, da tok nosilcev naboja od stripa proti ponoru ne teče ob površini polprevodnika pač pa preko notranjosti polprevodnika. Dinamična upornost FOXFET strukture je bila modelirana s pomočjo numeričnega odvajanja krivulje Vs/Is in kaže na zmanjšanje dinamične upornosti z večanjem toka stripa, kar je v skladju z rezultati meritev.

1. Introduction:

Silicon strip detectors are gaining importance for detection of particles in high-energy physics experiments. Such detectors are particularly suitable for detection of high-energy particles with high energy and spatial resolution. In recent years an increased number of applications in other fields - especially medicine - have emerged as well.

Strip detectors are built on very high resistivity (almost intrinsic) silicon wafers, enabling full substrate depletion at reverse voltages of few tens of volts. Such detectors are basically constructed by rows of diffused pn junctions (strips), with a spacing between the strips ranging from a few up to few tens of microns and a corresponding pitch (width of the strip + distance between the strips), depending on the required spatial resolution of the detector.

The particle hitting and crossing the detector generates electron-hole pairs that are following electric field established by reverse biased strip junction and are collected by the strip and the backplane electrodes. The signal can be detected as an increase of the reverse current, known as a DC method /1/. Instead of measuring the current increase, an AC method can be applied, where the signal is detected as a change in the collected charge /1/. This can be accomplished by placing a MOS electrode over the strip junction (Fig. 1) that is responding to the change in the strip charge by the change of a gate charge. For high resolution at low temperatures a direct coupling is suitable due to low input capacitance. The advantage of the first concept is also a well controlled leakage current. A charge sensitive preamplifier is very suitable as a feedback capacitance of charge amplifiers can be chosen to be very stable and thus minimize the noise of the system /1/.

Each strip should be appropriately biased in order to establish total depletion of the detector. One way of achieving this is by the use of polysilicon resistors /2/. This technique is well appreciated due to low susceptibility to oxide charges and operating conditions. On the other hand, additional processing steps increase de-

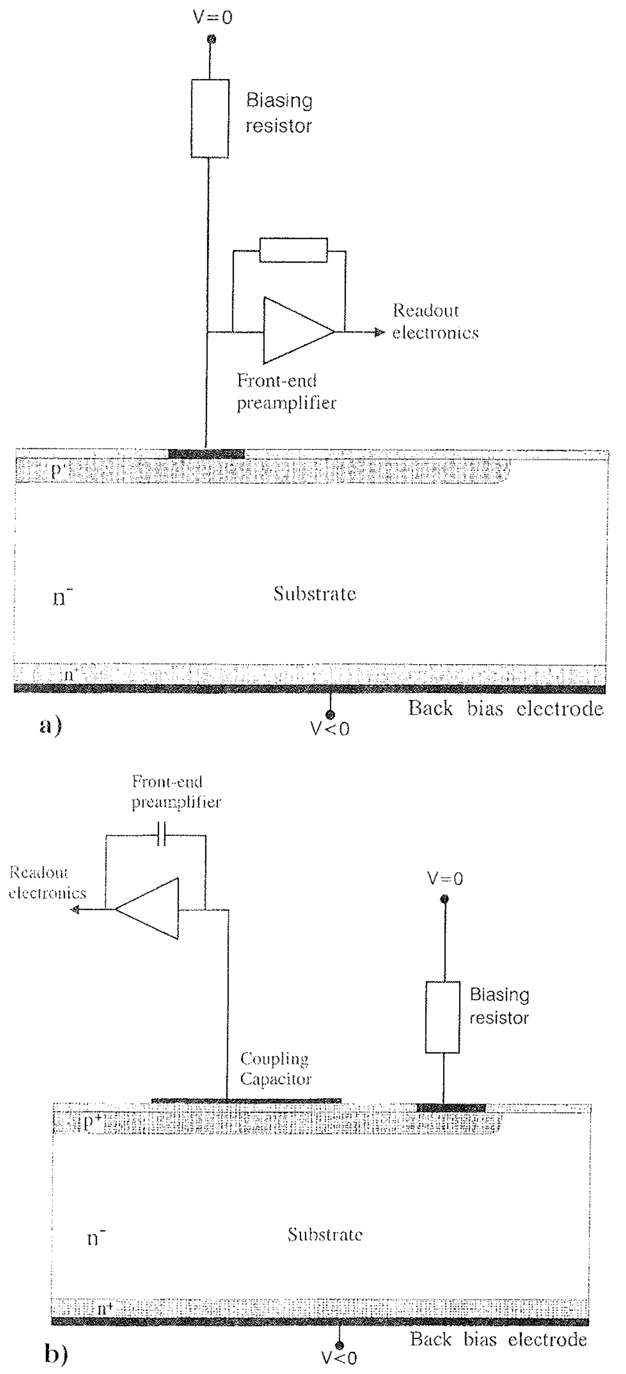


Fig. 1: Detector structure biasing schemes: DC coupled structure (a), AC coupled structure (b).

vice complexity and thus the cost of the device. Another possibility has been introduced by biasing the strips through the neighboring junction, that is reverse biased toward the substrate /3/. A depletion layer spreads from the biasing junction toward the strip, establishing a strip potential close to the biasing junction one. This is an inexpensive concept as no additional processing steps are required. However, depletion layer spreading from the biasing strip is significantly depending on the density of the oxide and interface charges. This is especially noticeable on high resistivity substrates.

An improvement of the reach-through concept is gained by placing a MOS electrode between the strip and the biasing junction /4,5,6/. This biasing structure is known as a FOXFET structure (Fig. 2). FOXFET is basically a MOSFET transistor with a gate over the field-oxide, drain acting as a biasing junction and source as a strip. However, its operation differs significantly from a usual MOSFET operation. First of all, FOXFET is built on high-resistivity substrates (> 1 kΩ·cm) resulting in significant depletion region spreading from the reverse biased drain/substrate junction and second, the source junction is at the same time used as an active detector structure. Furthermore, source junction does not have externally applied voltage, but attains a potential from depletion layer spreading from the reverse biased drain/substrate junction in a similar manner as the floating guard-ring termination structure for improvement of breakdown voltages of high-voltage devices /7/.

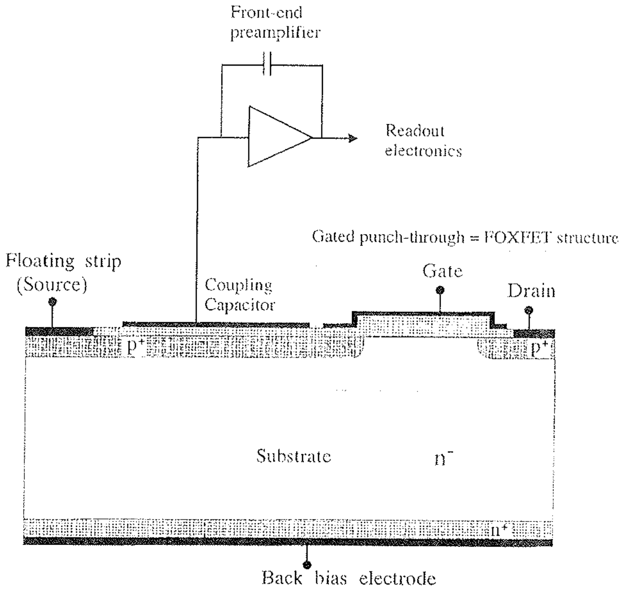


Fig. 2: FOXFET structure.

The requirement for proper operation of the detector built on high-resistivity material and biased through the FOXFET structure is to assure total depletion of the strip/substrate junction and at the same time enable high dynamic resistance of the FOXFET structure. In this paper a numerical device modeling approach has been used in order to analyze the operation of the FOXFET structure.

2. DEVICE MODELING OF THE FOXFET STRUCTURE

Most of the current understanding of the FOXFET structure originates from the measurements on the test structures and complete detector structures with FOXFET biasing /4,5/. In this work, a numerical device modeling approach has been applied to analyze and evaluate the influence of principal design parameters on the FOXFET operation. In the past, FOXFET structure has been modeled by either solving only the Poisson equation /4/

or by full drift-diffusion equations /8/. However, in both cases the strip junction has been externally biased by a voltage source (voltage boundary condition), which does not enable correct analysis of the FOXFET structure, as the strip junction should be left floating (unbiased). For proper modeling of a FOXFET structure, we have applied a zero current boundary condition to the strip junction, that enables analysis of FOXFET structure operation that is comparable to operation of a real device. Two-dimensional simulation with SPISCES /9/ device simulation program, incorporating full drift-diffusion model, has been used for this purpose.

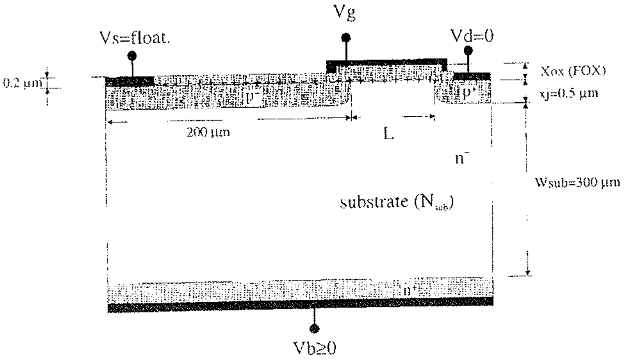
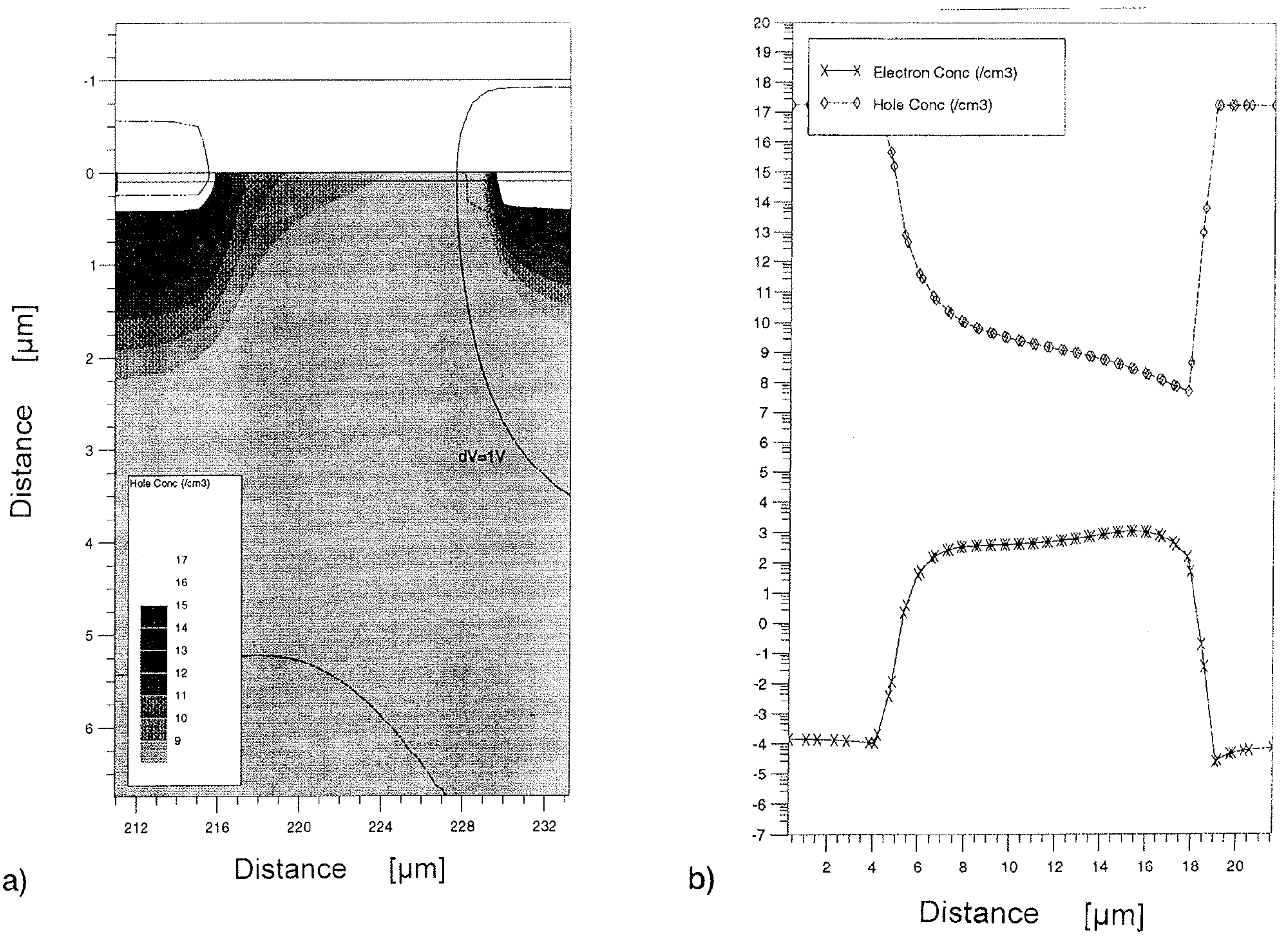


Fig. 3: Dimensions and parameters of the simulated FOXFET structure.

The dimensions of the simulated structure are shown in Fig. 3, while typical simulation parameters were: substrate doping (n-type) concentration $N_{sub} = 3.8 \cdot 10^{11} cm^{-3}$ (resistivity 10 kΩ.cm), p-type junction with Gaussian doping profile with surface doping concentration $N_{surf} = 1.10^{18}$ cm^{-3} and junction depth $x_j = 0.5$ μm, oxide thickness $x_{ox} = 1$ μm with fixed oxide charges of $Q_F/q = 1.10^{11}$ - 8.10^{11} cm^{-2}, substrate thickness $W_{sub} = 300$ μm, channel lengt L = 13 μm and carrier lifetimes $\tau_n = \tau_p = 0.5$ msek.

3. OPERATION OF THE FOXFET STRUCTURE

Normal operation of the FOXFET structure is obtained by applying reverse bias between the drain and the backplane (drain connected to the ground, backplane to a positive potential). As the strip can in practice be very long (few centimeters), an additional current drawn by the strip can be modeled by an increased injected current using a current source generator attached to a strip contact. Gate contact is usually connected to the drain contact, drain junction thus acting similar to a junction equipped with a field-plate termination /7/. By varying the gate voltage, depletion layer spreading from the drain to the strip junction is modulated and thus a control over the strip potential is obtained.



a)

b)

Fig. 4: FOXFET structure with zero oxide charge at 30 volts reverse bias: equipotential lines and hole concentration (a), hole and electron concentrations at the semiconductor/oxide interface (b).

3.1 Influence of the oxide charges

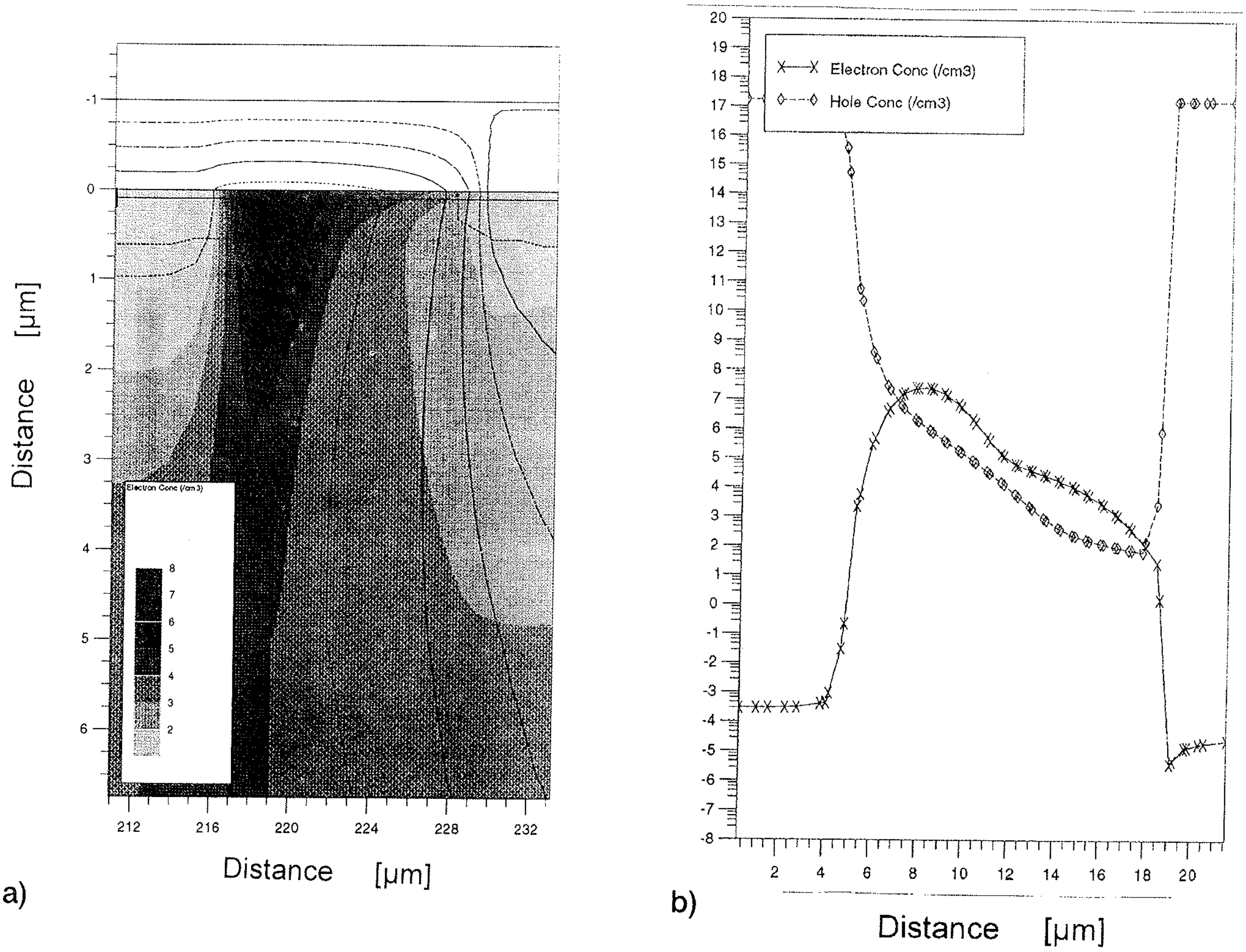
Operation of the FOXFET structure depends strongly on the content of the oxide and interface charges. This is especially significant as already a small amount of oxide charges induces a charge at the semiconductor/oxide interface which can be significant comparing to charge obtained by a reverse biased junction (depleted substrate area).

If no oxide charges are assumed (only a theoretical case), depletion layer width calculated for an abrupt one-dimensional structure with $N_{sub}=3.8\cdot10^{11}cm^{-3}$ at built-in voltage is more than 40 μm. For typical channel lengths of about 10 μm this means that the strip/drain junctions are in reach-through condition already at no reverse voltage applied. The area between the drain and the strip is completely depleted of carriers and the strip potential is close to the drain potential for increased drain/backplane reverse bias. Fig. 4 shows equipotential lines and hole concentration in the channel region as well as electron and hole concentrations at the interface for a structure without oxide charges at 30 volts of reverse bias and zero gate voltage.

Electron concentration is negligible while hole concentration is increased in the channel region at the surface. Potential of the strip is practically identical to the drain one, which does not enable proper operation of the FOXFET structure. However, an increased strip/drain voltage can be obtained by a positive gate voltage, increasing electron concentration at the surface and thus slowing depletion layer spreading from drain to strip junction.

The presence of oxide charges significantly alters the behavior of the device. Several kinds of charges are present in the oxide, depending on the starting material, processing and operation of the device /10/. However, altogether they are of a positive sign /10/, inducing in n-type semiconductor accumulation of electrons at the oxide/semiconductor interface. Accumulation of electrons acts similar to locally increased donor doping concentration. This results in reduced depletion layer spreading from the drain to the strip junction (depletion layer increases inversely proportional to the square root of the doping concentration) and thus a potential difference between the junctions is increased.

Fig. 5 shows equipotential lines and electron concentration for the same operating conditions as in Fig. 4 but with inclusion of fixed oxide charges of $Q_F/q=10^{11}$ cm^{-2}. Instead of a hole concentration, in this case an accumulation of electrons at the surface is shown. As a consequence, equipotential lines are denser between the drain and the strip junction and the strip potential differs



a) b)

Fig. 5: FOXFET structure with oxide charge $Q_F/q=10^{11}$ cm^{-2} at 30 volts reverse bias: equipotential lines and electron concentration (a), hole and electron concentrations at a semiconductor/oxide interface (b).

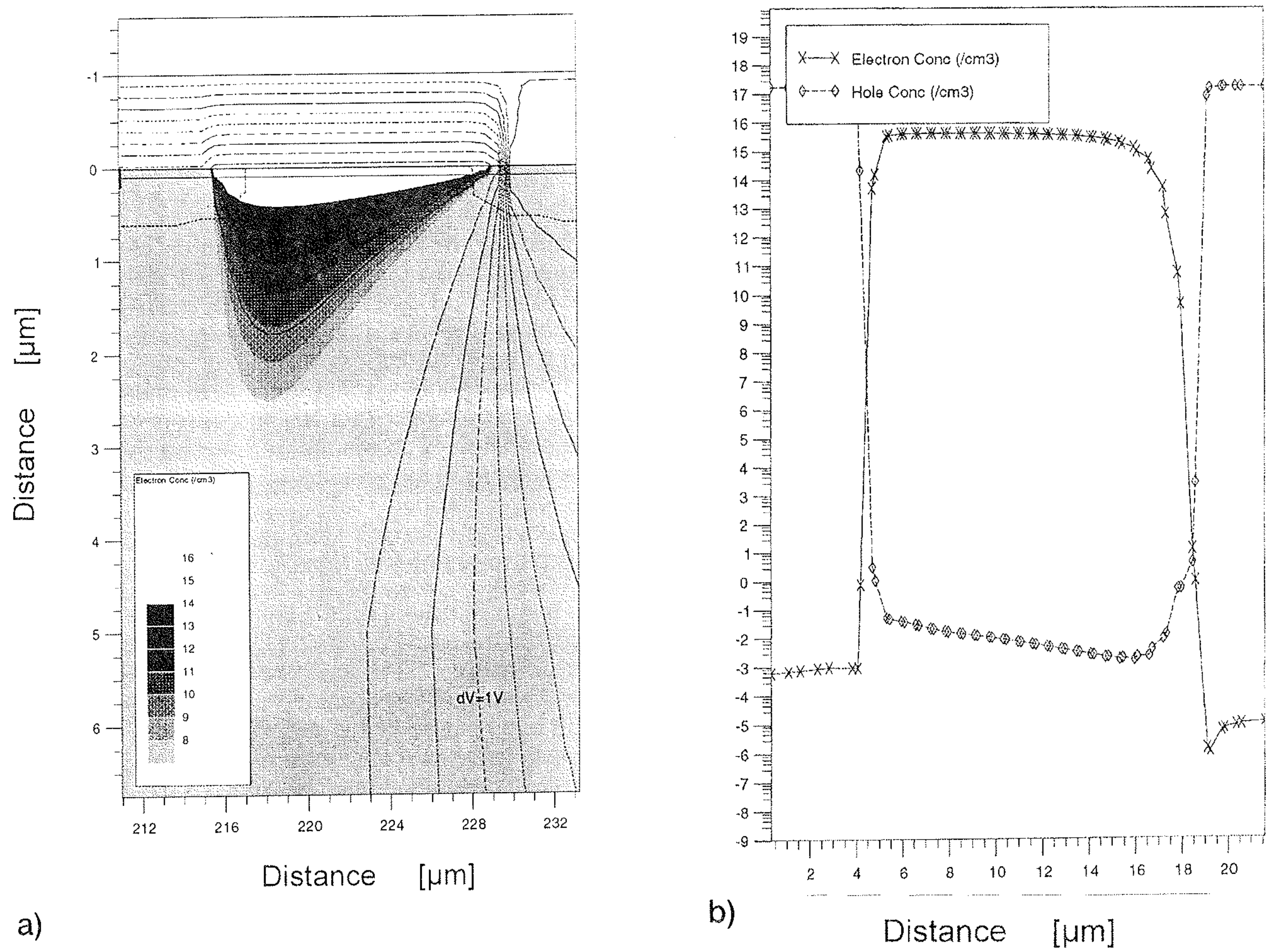


Fig. 6: FOXFET structure with oxide charge $Q_F/q=5.10^{11}$ cm^{-2} at 30 volts reverse bias: equipotential lines and electron concentration (a), hole and electron concentrations at the semiconductor/oxide interface (b).

from a drain one for a few volts. Electron concentration is increased especially at the strip junction as at the drain junction it is modulated by depletion layer spreading from the drain junction.

A further increased density of oxide charges forms significant accumulation of electrons at the interface, as shown in Fig. 6 for fixed oxide charge density of 5.10^{11} cm^{-2}. Equipotential lines are squeezed at the drain junction area and a reach-through between the drain and the strip depletion layers occurs in the bulk of the device, few microns from the surface.

Increase of the strip potential with increasing drain/backside reverse voltage can be to a first approximation expressed from simple depletion layer spreading from the drain junction, that should be modulated by the influence of the gate voltage as well as the oxide charges. Following 1D Poisson equation with depletion approximation, the strip voltage is given by

$$V_s = L \cdot \sqrt{\frac{2 \cdot q \cdot N_{eff}}{\varepsilon_0 \cdot \varepsilon_{Si}} \cdot (V_{bi} + V_{rev})} \qquad (1)$$

where N_{eff} is an effective doping concentration that should be a function of the gate voltage and the oxide charges $N_{eff} = f(V_g, Q_F)$.

Modeled FOXFET structure for different oxide charges in Fig. 7 indeed shows a square root behavior of a strip potential with increasing drain/backside bias as predicted by equation 1. Furthermore, Fig. 7 demonstrates that after a certain oxide charge density ($>3.10^{11}$ cm^{-2}) the strip potential changes very weakly for further increased oxide charge densities. The reason is depletion layer spreading, avoiding the electron accumulation region at the oxide/semiconductor interface and reaching the strip junction from the bulk of the device.

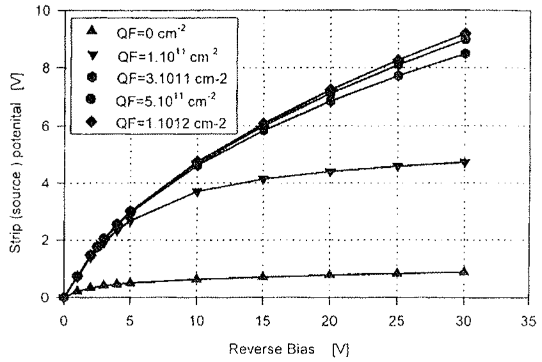


Fig. 7: Strip potential as a function of drain/backside reverse voltage for oxide charge densities of $Q_F/q=10^{11}cm^{-2}$, $3.10^{11}cm^{-2}$, $5.10^{11}cm^{-2}$, 1.10^{12} cm^{-2} at $V_g=0V$.

3.2 Influence of the gate voltage

A similar square root behavior as from $V_s/V_{rev}(Q_F)$ is obtained by changing the gate voltage as shown in Fig. 8 for oxide charge density of $Q_F/q=5.10^{11}$ cm^{-2}. Positive oxide charges, located just above the oxide/semiconductor interface, induce accumulation of electrons at the interface. This results in highest strip potential at $V_g=0V$. The influence of oxide charges can be reduced by applying a negative gate voltage. If gate voltage is such that completely neutralizes the effect of positive oxide charges, the drain depletion layer is free to spread toward the strip junction, resulting in strip potential equal to the drain one as already shown in Fig. 4. For fixed oxide charges of $Q_F/q=5.10^{11}$ cm^{-2} and oxide thickness of 1 μm, this situation can be approximately evaluated by equation

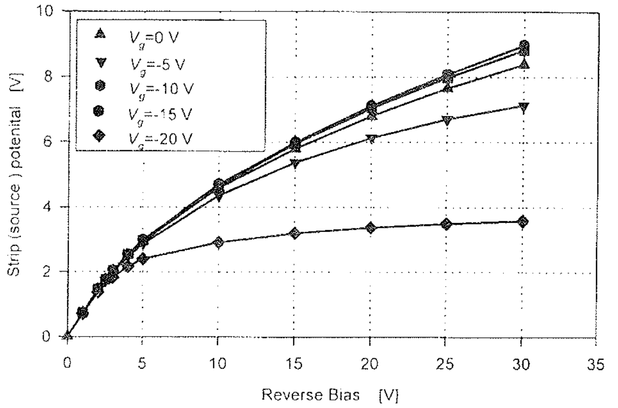


Fig. 8: Strip potential as a function of drain/backside reverse voltage for gate voltages $V_g=0$ to $-20V$ and oxide charge density of $Q_F/q=5.10^{11}$ cm^{-2}.

$$\Delta Vg = \frac{Q_F}{C_0} \approx 23 \text{ volts} \qquad (2)$$

where $C_0=(\varepsilon_0 \cdot \varepsilon_{0x})/x_{0x}$. This result is in good agreement with simulation results. Fig. 8 further shows weak dependence of gate voltage at low applied gate voltages. These voltages are too small to considerably reduce the electron accumulation layer at the oxide/semiconductor interface.

3.3 Current flow in the FOXFET structure

Since the strip junction is floating (its potential depends on depletion layer spreading from the reverse biased drain/substrate junction), and is at the same time reverse biased toward the substrate, it needs to be in a certain point forward biased in order to satisfy a condi-

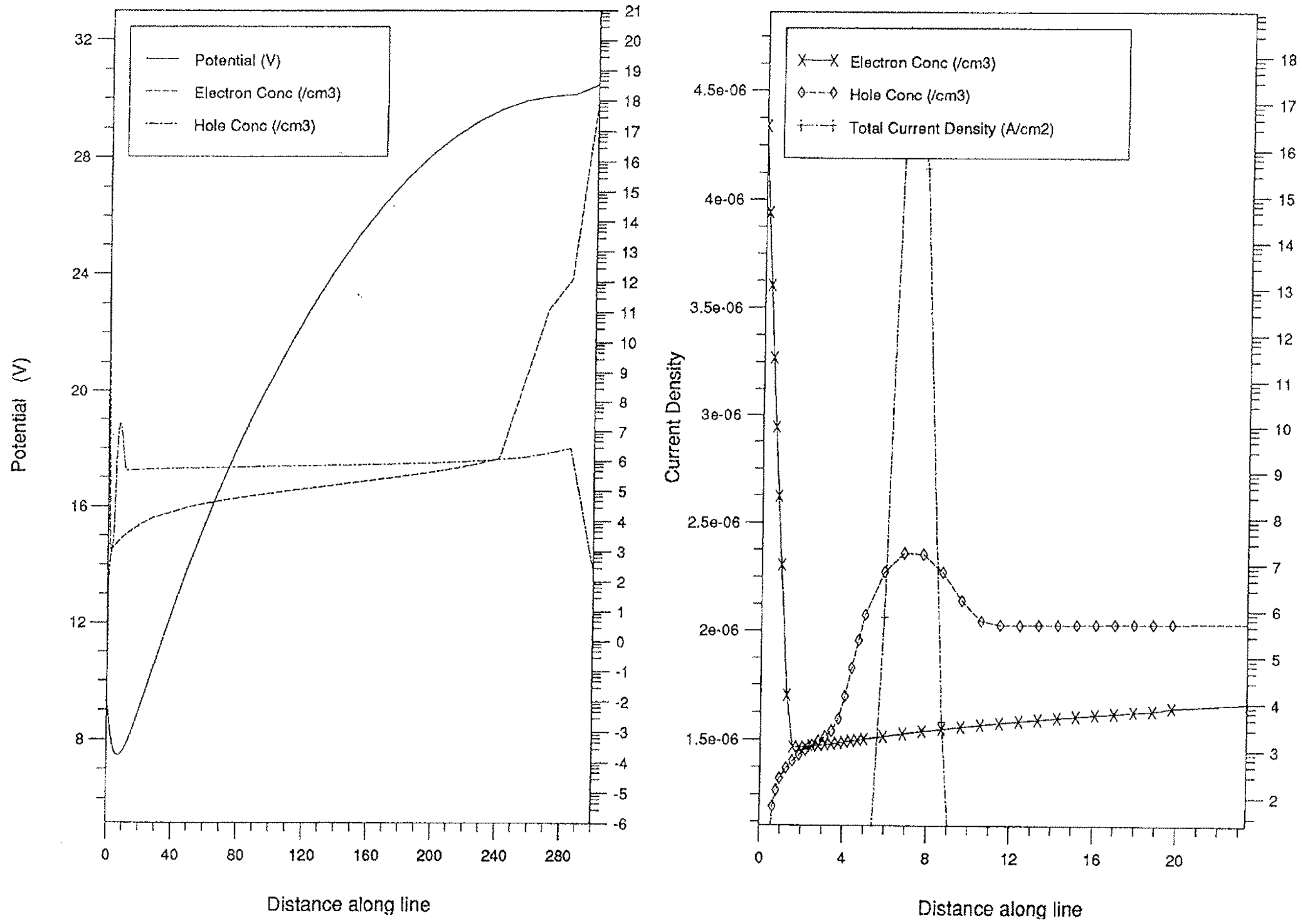


Fig. 9: Potential, total current density and hole and electron concentrations for a vertical cross-section of a FOXFET structure with $Q_F/q=5.10^{11}$ cm^{-2} at 30 volts reverse voltage.

tion of zero current sum of currents entering and escaping the strip (first Kirchoffs law). As a result, reverse current entering the strip junction (holes in n-type semiconductor) is injected back into the substrate and flows through the FOXFET into the drain junction. Current conduction in a FOXFET structure is similar to conduction in a punch-through pnp structure, which is assumed to be governed by thermionic emission /11/. However, thermionic emission is typical for punch-through structures with highly doped base regions (BARRIT structures, for example) /7/, while in our case, the channel region (base) is very weakly doped. Furthermore, the current flow through the FOXFET is limited by the reverse current collected by the strip junction. As a result, it can be assumed that no thermionic emission is taking place in conduction of a FOXFET structure, but rather "simple" drift-diffusion rules the conduction of the carriers /12/. Drift component of the current prevails in the drain region as can be also deduced from the density of the equipotential lines in figures 4 to 6, while in the strip region of the FOXFET structure electric field is very weak. As a result, the carriers in the strip region move by diffusion.

Figure 9 presents potential, total current density and hole and electron concentrations in a vertical cross-section of a FOXFET structure at the end of the strip junction. The potential bends at the oxide/semiconductor interface, reverse biasing the strip/substrate junction in this part of the FOXFET structure. A closer look reveals (Fig. 9b) that this is due to the electron accumulation layer, which is still significant in this part of the structure. As a consequence, strip junction is forward biased toward the bulk of the FOXFET structure, which is obvious from an increased hole concentration located few microns from the interface. The current is thus not flowing at the oxide/semiconductor interface but rather few microns from the interface, avoiding the electron accumulation region. This is obvious also from high total current density in Fig. 9 located few microns from the interface.

3.4 Dynamic resistance

One of the most important parameters of the FOXFET structure is its resistance, or better its dynamic resistance, as this parameter determines the proper strip biasing as well as affects the noise of the detector. Dynamic resistance is defined as $Rd = (\partial V_S)/(\partial I_S)$. In general, resistances over 100 MΩ can be obtained at very low currents /6/. By approximating the dynamic resistance of the FOXFET structure by a dynamic resistance of an ideal pn diode, the resistance decreases approximately inversely with the increase of the strip current /6/. This can result in unacceptably low dynamic resistance at high strip currents.

Dynamic resistance has been modeled by a current source attached to the strip. Increasing the strip current by a current source at 30 volts of drain/backside reverse bias a Vs/Is curve is obtained. This curve can be numerically differentiated to calculate the dynamic resistance. Figure 10 shows extracted dynamic resistance for gate voltages from 0 to -15 volts. It should be noted that the scale is in [Ω .µm] and [A/µm] due to the use of a 2D simulation. No change in dynamic resistance is obtained for small strip currents while increasing strip current results in a reduction of dynamic resistance with a slope of approximately 0.8. A reduced slope at high currents is due to the SCLC current conduction effect /12/.

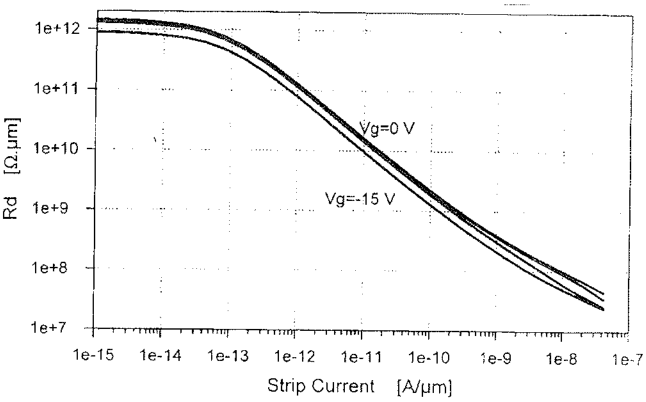


Fig. 10: Dynamic resistance of the FOXFET structure with 30 V drain/backside bias, $Q_F/q=5.10^{11}$ cm^{-2} and $x_{OX}=1$ µm.

4. CONCLUSIONS

This work presented analysis of a FOXFET structure for biasing detector structures built on high-ohmic substrates by the aid of numerical device modeling. A general purpose two-dimensional device simulation program SPISCES, solving drift-diffusion equations has been used for this purpose. In order to model FOXFET structure properly, the floating strip junction was connected to a zero current source. The current source connected to the strip junction was further used to extract dynamic resistance of the structure.

Modeling has revealed that oxide charges, forming an accumulation layer of carriers at the semiconductor/oxide interface play the most significant role in determination of the strip potential. However, gate voltage can be applied to balance the influence of the oxide charges. It has been further shown that due to the formation of an accumulation layer, the carriers collected by the strip junction flow to the drain through the bulk, avoiding the accumulation layer. Few equipotential lines in the strip region indicate that carriers in this region move towards drain by diffusion and by drift in the second half of the channel region.

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