Distortion of the CV characteristics by a high current

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1. Introduction

CV measurements with the strip detectors are usually performed between the sensor backside and the bias rail in Cs-Rs mode. Cs represents the capacitance between all strips and the backside in the depleted volume while the Rs represents all bias resistors, Rbias, connected in parallel plus the resistance of the un-depleted bulk. It was observed experimentally that the results may be distorted by a high sensor current. The aim of this Note is to understand possible reasons for this distortion.

1. Generation current model

High current may be interpreted as the presence of an additional resistor with a relatively low value in the circuit diagram. If the current is mostly generated inside the depleted volume then an additional resistor, Rg, appears in parallel to the capacitance of the depleted part of the sensor, C, as shown in the diagram presented in Fig.1.

Fig. 1. Circuit diagram for the generation current model

Here Rb denotes an effective resistance consisting of the bias resistors connected in parallel plus the resistance of the un-depleted bulk. As shown in the appendix the Cs and Rs values for the above circuit measured at frequency *f* are the following:

$C\_{s}=C\frac{1+Q\_{p}^{2}}{Q\_{p}^{2}}$ , (1)

$R\_{s}=R\_{b}+\frac{R\_{g}}{1+Q\_{p}^{2}}$ . (2)

Here Qp = ωCRg and ω=2*f*. Obviously Cs > C and Rs > Rb. If Rg→∞ then Qp→∞, Cs→C and Rs→Rb. If Rg→0 then Qp→0, Cs→∞ and Rs→Rb. The maximum value of Rs equal to Rb+Rg/2 is achieved when Qp=1.

1. Leakage current model

If the current is mostly due to leakage over the sensor edge then an additional resistor, Rl, appears in parallel to C and Rb connected in series as shown in the diagram presented in Fig.2.

Fig. 2. Circuit diagram for the leakage current model

As shown in the appendix the Cs and Rs values for the above circuit measured at frequency *f* are the following:

$C\_{s}=C\frac{1+D\_{s}^{2}}{ρ^{2}D\_{s}^{2}}$ , (3)

 $R\_{s}=ρ(R\_{b}+\frac{R\_{l}}{1+D\_{s}^{2}}$) . (4)

Here **=Rl/(Rl+Rb) and Ds=ωC(Rl+Rb). Obviously ** < 1 and Cs > C. If Rl→∞ then ** → 1, Ds→∞, Cs→C and Rs→Rb. If Rl→0 then ** → 0, Ds→ ωCRb, Cs→∞ and Rs→0.

1. Application to the experimental data

The above models were used to interpret the experimental data obtained with un-irradiated sensor w01-bz4-p4 produced within the ATLAS upgrade program. The sensor has 104 strips with the total area of ~0.8x0.8 cm2 and a thickness of ~300 m. The bias resistors have a value of ~2 M. Connected in parallel they give the resistance, Rb, of ~2000 k/100=20 k. The CV measurements were made at a frequency of 10 kHz. Fig.3 shows the current, Cs and Rs values vs bias voltage.



Fig.3. The current, Cs and Rs vs bias voltage for the strip mini-sensor w01-bz4-p4.

Above 200V the sensor is fully depleted with Cs and Rs reaching a plateau. Above 500V the current grows steeply and both Cs and Rs increase with bias.

It was assumed that the additional resistance (Rg or Rl in Figs 1 and 2) can be estimated from the IV curve as the dynamic resistance: Rdyn = dU/dI. It is shown in Fig.4 vs bias. At low Ubias it has a very high value of ~105 M but above 500 V it drops, first sharply and then more slowly, to a few Mlevel. Note however that even the lowest Rdyn is still much higher than the Rs plateau value of ~ 20 k.

Verification of the models was made as follows. The average Cs and Rs values between 200V and 260V were assumed to represent C and Rb in the diagrams shown in Figs 1 and 2. The Rg for the first model and Rl for the second one were set to the Rdyn value. Then, using Equations (1) – (4), Cs and Rs were calculated above 200 V and compared with the experimental data. The results are presented in Figs 5 and 6.



Fig.4. The dynamic resistance dU/dI extracted from the IV curve



Fig.5. Cs: measured experimentally and calculated from the two models.



Fig.6. Rs: measured experimentally and calculated from the two models.

1. Discussion

As seen in Figs 5 and 6 both models reproduce the experimental data reasonably well. It is not surprising that both models give very similar results. As mentioned above, the Rb of ~20 k is much smaller than Rdyn > 1 M. In this case it is not important whether Rdyn is connected in parallel to the whole C - Rb chain as in Fig. 2 or to the capacitance alone as in Fig.1. Mathematically it can be explained as follows. The value of ** in Equations (3) and (4) is always very close to 1 and the value of Ds is close to ωCRl. In this situation Equations (3) and (4) revert to Equations (1) and (2) with Rl in place of Rg.

In the above example the additional resistor value set to dU/dI explains the experimental data quite well. However this is not always the case. Moreover the high current may have both generation and leakage components and the equivalent circuit diagram should be a combination of those presented in Figs 1 and 2 and include both Rg and Rl. The Cs and Rb values in this case can be found combining Equations (1) – (4). It was mentioned already that for both models Cs is larger than the actual capacitance C. It is easy to demonstrate that the same is true for the circuit including both Rg and Rl.

First, the part of the circuit containing Rg (shown in Fig.1) can be converted into an equivalent Cs - Rs chain using Equations (1) and (2). Let us denote the resulting parameters as Csg and Rbg. Then it can be complemented by Rl connected in parallel. The final Cs and Rs values can be found from Equations (3) and (4) using Csg in place of C and Rbg in place of Rb. Clearly: Cs > Csg > C. Thus whatever additional resistor (or both of them) should be included in the equivalent diagram the resulting Cs is always larger then C.

1. Conclusions

The distortion of the experimentally measured Cs and Rs parameters can be explained as resulting from an additional resistance with a relatively low value, which appears because of a high current. The equivalent circuit diagram can be the one shown in Fig.1 or Fig.2 or a combination of both. In the example presented in this Note the value of the additional resistance was assumed to be equal to the dynamic resistance following from the IV characteristic, Rdyn = dU/dI. This allowed calculation of the Cs and Rs values above their plateau for two simple models. Both of them gave very similar results, which agreed well with the experimental data. In the general case finding the additional resistor value is not so straightforward. Moreover the actual equivalent circuit may include both Rg and Rl. In all cases however the resulting Cs value is higher than the actual capacitance C. Thus a high leakage current should always lead to an increase in the measured capacitance.

Appendix

To find the values of Cs and Rs for any circuit one has to calculate its complex impedance Z and compare it with

$Z=R\_{s}-\frac{j}{ωC\_{s}}$ (A1)

1. **Generation current model**

The impedance of the circuit shown in Fig.1 is the sum of Rb and the impedance, Zp, of C in parallel to Rg. The conductance of this circuit Gp=1/Zp can be written as

$G\_{p}=\frac{1}{R\_{g}}+jωC=\frac{1+jQ\_{p}}{R\_{g}}=\frac{1+Q\_{p}^{2}}{R\_{g}\left(1-jQ\_{p}\right)}=\frac{1}{Z\_{p}}$ . (A1.1)

Here Qp = ωCRg is the quality factor of the C-Rg circuit, ω=2π*f*, where *f* is the measurement frequency. Thus the whole impedance can be written as

$Z=R\_{b}+\frac{R\_{g}}{1+Q\_{p}^{2}}-\frac{jQ\_{p}^{2}}{ωC\left(1+Q\_{p}^{2}\right)}$ . (A1.2)

Comparing Equations (A1.2) and (A1) one obtains Equations (1) and (2). Note that Cs does not depend on Rb but only on Rg. Cs is close to C if Qp2 >> 1. To what extent Rs is simultaneously close to Rb depends on the relation between the Rg and Rb values.

1. **Leakage current model**

The impedance, Z, of the circuit shown in Fig.2 is Z1Z2/(Z1+Z2), where Z1=Rl and Z2 = Rb + 1/(jC). It can be written as

$Z=\frac{R\_{l}\left(R\_{b}+^{1}/\_{jωC}\right)}{R\_{l}+R\_{b}+^{1}/\_{jωC}}=R\_{l}\frac{1+jωCR\_{b}}{1+jD\_{s}}$ , (A2.1)

where Ds = (Rl+Rb)C is the dissipation factor of the circuit consisting of C, Rb and Rl connected in series. Multiplying the numerator and denominator in Equation (A2.1) by 1-jDs one obtains

$Z= R\_{l}\frac{1+R\_{b}\left(R\_{l}+R\_{b}\right)ω^{2}C^{2}}{1+D\_{s}^{2}}-jωC\frac{R\_{l}^{2}}{1+D\_{s}^{2}}$ . (A2.2)

Introducing the parameter ** = Rl/(Rl+Rb) Equation A(2.2) can be rewritten as

$Z=ρ\left(R\_{b}+\frac{R\_{l}}{1+D\_{s}^{2}}\right)-\frac{jρ^{2}D\_{s}^{2}}{ωC\left(1+D\_{s}^{2}\right)}$ . (A2.3)

Comparing Equations (A2.3) and (A.1) one obtains Equations (3) and (4).