DETERMINATION OF INTERFACE TRAP DENSITY IN UNIPOLAR STRUCTURES USING QUASISTATIC C–V METHOD

Pavol Písečný — Milan Ţapajna — Ladislav Harmatha — Andrej Vrbický

The design and realization of computer controlled measurement for determination of the trap density on the insulator-semiconductor interface ($D_{it}$) using quasistatic $C–V$ method is described. This method is simple, nevertheless, it is the most accurate technique for $D_{it}$ determination in comparison to other ones. Using appropriate theoretical analysis, one can also obtain the energy distribution of interface trap density in the bandgap. In the experiment, two series of samples were used: (1) high-quality MOS structures prepared by different oxidation processes and (2) samples irradiated by 305 MeV Kr$^+$ and 710 MeV Bi$^+$ ions with different fluencies. From pulsed MOS capacitor measurement (the so-called $C–t$ technique), surface generation velocity $S_g$ was evaluated and, subsequently, the interface capture cross-section was calculated. All the results are discussed with regard to the amount of interface defects as well as their electrical activity.

Keywords: MIS structure, quasistatic $C–V$ measurement, interface trap density

1 INTRODUCTION

The measurement of the low frequency capacitance-voltage ($C–V$) curve of a MIS (metal-insulator-semiconductor) structure is one of the methods for determining the energy distribution of the insulator-semiconductor interface trap density [1]. This parameter is related to the quality of the gate stack and its interface with underlying semiconductor. The interface traps create energy levels in the bandgap of the semiconductor, thus they act as generation-recombination centres. The origin of these defects yields from:

- structural defects, for example lattice discontinuity, silicon or oxygen vacancy created during oxidation
- metal impurity, for example Na, Pt, Au,
- defects induced by irradiation which breaks the atomic bonds in the crystal.

The present unipolar technology requires the value of $D_{it} < 10^{15}$ m$^{-2}$ eV$^{-1}$. The problem of the interface quality becomes essential with regard to present scale decreasing and replacement of silicon dioxide with a high-$\kappa$ material insulator layer. There are many ways how to measure the low frequency $C–V$ curve, however, the quasistatic charge-voltage method is mostly used at present. One of the main advantages of the low frequency $C–V$ method is that the distribution of $D_{it}$ is determined over the full width of the bandgap.

2 THEORY

For determining the energy distribution of the interface trap density it is necessary to know the dependence of band bending on the gate bias $\varphi_S = f(V_G)$. This dependence could be obtained from integration of the measured low frequency $C–V$ curve and is given as [2]

$$\varphi_S = \int_{V_{FB}}^{V_G} \left(1 - \frac{C(V_G)}{C_I} \right) dV_G,$$

(1)

where $V_{FB}$ is the flat-band voltage and $C_I$ is the insulator layer capacitance. The $\varphi_S$ is linearly proportional to the energy in the bandgap

$$E - E_i = q(\varphi_S - \varphi_F),$$

(2)

where $\varphi_F$ is the Fermi level in the semiconductor. The capacitance of the interface trap is given as [1]

$$C_{it} = \left(\frac{1}{C_{L,F,real}} - \frac{1}{C_I}\right)^{-1} - \left(\frac{1}{C_{L,F,ideal}} - \frac{1}{C_I}\right)^{-1},$$

(3)

where $C_{L,F,real}$ is the measured capacitance and $C_{L,F,ideal}$ is the capacitance of the ideal MOS structure obtained from the theoretical low frequency dependence $C = f(V_G)$ [2]. The density of interface trap is given by [1]

$$D_{it} = \frac{1}{q^2 C_{it}}.$$
Hence, one can obtain the energy distribution of interface trap density $D_{it} = f(E - E_i)$ in the semiconductor bandgap by linking the values of energies from eq. (2) with the values of $D_{it}$ from eq. (4) at the same gate bias. Performing $C$-$t$ measurement [2] to acquire the surface generation velocity $S_g$, the magnitude of the interface capture cross-section $\sigma_{ni}$ could be determined, which defines the electrical activity of traps as [3]

$$S_g = \sigma_{ni} v_{th} D_{it},$$

where $v_{th}$ is electron thermal velocity (for silicon $v_{th} = 1 \times 10^5 \text{ms}^{-1}$).

### Table 1. Parameters of oxidation process

<table>
<thead>
<tr>
<th>Sample</th>
<th>FA 2-4</th>
<th>FA 3-2</th>
<th>PY</th>
<th>D0,D1,D2,D8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation ambient</td>
<td>$O_2 + 3% \text{HCl}$</td>
<td>$O_2 + \text{H}_2$</td>
<td>dry $O_2$</td>
<td>dry $O_2$</td>
</tr>
<tr>
<td>Oxidation temperature (°C)</td>
<td>1050</td>
<td>1000</td>
<td>1050</td>
<td>1050</td>
</tr>
<tr>
<td>Oxide layer thickness (nm)</td>
<td>80</td>
<td>76</td>
<td>73</td>
<td>100</td>
</tr>
</tbody>
</table>

3 MEASUREMENT SET-UP

For quasistatic measurement we utilized a $C$-$V$ meter Keithley 595 which implements the charge-voltage method (Fig. 1). In this method, a linear step voltage is applied to the gate of the MIS structure and subsequent charge transfer from the response to the voltage increment is measured (Fig. 2) [4]. Another way of quasistatic measurement is the current-voltage method. However, the charge-voltage technique has a better noise resistance in comparison with the current-voltage method. The next advantage arises from application of $Q$/$t$ current, from which it is possible to distinguish the equilibrium of measurement. For controlling the measurement and data visualization, program ZENON was designed. The input parameters of the measurement are very important for the low-frequency $C$-$V$ curve. The main parameter is the rate of the voltage step (voltage step and delay between single steps), which provides retrieving of the structure to the equilibrium state and thereby influences the magnitude of the oxide capacitance in inversion. Note that equation (3) can be applied only in equilibrium. For cal-
FA 2-4

Dry O

1220

Posed to heavy-ion (Kr+ + H2) irradiation with different fluencies in order to damage the SiO2-Si interface. From the measurements described above, the cross-section of radiation defects was evaluated. The VFB and Sg values are obtained from high-frequency C−V and C-t measurements, respectively [5].

An n-type, antimony doped, (100)-oriented homogeneous wafer with resistivity of 2–5Ωcm and thickness 300µm was used as a substrate of all structures. The SiO2 gate layer of all structures was prepared by thermal oxidation listed in Tab. 1. Gates were prepared by vapour deposition of Al with thickness 1.3µm and patterned photolithographically. The samples were annealed in N2 + H2 at 460°C for 20 minutes after manufacturing. After these steps, samples D1, D2 and D8 were exposed to various irradiations (Tab. 3).

Figures 3, 5 and 7 show experimental low-frequency C−V curves of structures FA 2-4, FA 3-2 and PY, respectively. As one can see, capacitance in strong inversion is equal to that in accumulation (n-type substrate), hence according to equations described in section 2, differences between experimental data and fitted theoretical ones yield the energy distribution of Dit in the band gap (shown in figures 4, 6 and 8).

For comparison, the interface trap density Dit was determined as mean values at ±0.1 eV near the middle of the band gap (Tab. 2). The lower Dit of the structure FA 2-4 made in O2 + 3% HCl in comparison with the structure FA 3-2 made in O2 + H2 is probably due to gettering effects of Cl atoms at the Si−SiO2 interface. It is interesting that structure FA 2-4 with interface trap density as low as 8.1 × 10^{13} m^{-2} eV^{-1} exhibits a higher value of surface generation velocity than sample FA 3-2 (with Dit = 4.1 × 10^{14} m^{-2} eV^{-1}). This effect is caused by changed electrical activity of interface traps regarding to the approximately 3 times higher interface capture cross-section of structure FA 2-4. From these results it is obvious that several methods have to be employed for complex study of interface.

Structure PY (Fig. 7) prepared by present technology in dry O2 shows excellent flat-band voltage (VFB = −0.01 V) and low value of Dit. It indicates a negligible amount of effective defect charge in SiO2 layer and at its interface with silicon. However, Sg determined from C-t measurement has an exceptionally high value. This issue is reflected in a large capture cross-section of interface traps or, in other words, the concentration of traps at the interface is low but they act as efficient generation-recombination centers, thereby causing carrier mobility lowering in the channel. For their sufficient suppressing by process optimization it is necessary to use both equilibrium as well as non-steady state measurement methods.

Figure 9 shows low-frequency C−V curves of non-irradiated (D0) and irradiated (D1, D2 and D8) samples, where in the second case various ion masses and fluencies were used (Tab. 3). The values of Dit in Tab. 3 were determined at 0.22 eV over the middle of the bandgap (Fig. 10).

![Fig. 5. Low-frequency C−V curve of structure FA 3-2.](image)

![Fig. 6. Energy distribution of interface trap density of structure FA 3-2.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>FA 2-4</th>
<th>FA 3-2</th>
<th>PY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation ambient</td>
<td>O2 + HCl</td>
<td>O2 + H2</td>
<td>dry O2</td>
</tr>
<tr>
<td>VFB (V)</td>
<td>−0.13</td>
<td>−0.69</td>
<td>−0.01</td>
</tr>
<tr>
<td>Dit (m−2eV−1)</td>
<td>8.1 × 10^{13}</td>
<td>4.1 × 10^{14}</td>
<td>1.6 × 10^{14}</td>
</tr>
<tr>
<td>Sg (ms−1)</td>
<td>1.2 × 10^{−4}</td>
<td>6.6 × 10^{−5}</td>
<td>1.5 × 10^{−3}</td>
</tr>
<tr>
<td>τq (µs)</td>
<td>280</td>
<td>1220</td>
<td>1200</td>
</tr>
<tr>
<td>σm (m²)</td>
<td>8.15 × 10^{−24}</td>
<td>2.93 × 10^{−24}</td>
<td>9.37 × 10^{−25}</td>
</tr>
</tbody>
</table>

calculation of the interface trap density energy distribution the program ARTEMIS was designed.

**4 EXPERIMENT AND RESULTS**

To verify the function of the designed measurement set-up and to demonstrate the method feasibility, two series of samples were analyzed. In the first one, high-quality MIS structures with SiO2 as an insulating layer were fabricated by thermal oxidation in different ambient and temperature. The second series of samples were exposed to heavy-ion (Kr+, Bi+) irradiation with different
The radiation changes interface trap density $D_{it}$ which can be observed on the slope of $C-V$ curves in depletion and weak inversion region. Also the flat-band voltage $V_{FB}$ shifts to a higher negative value with increasing fluency (compare D1 with D2). From the experimental data one can conclude that the increase of fluency and ion mass induces a growth of $D_{it}$ and $S_g$, thus the interface deteriorate. Nevertheless, irradiated MOS structures retain their basic capacitance behavior even after high-energy radiation. One could speculate about the nature of the interface traps. Non-irradiated sample (D0) and sample D1 have interface capture cross-sections which are very close to counterpart samples D2 and D8 with approximately one order higher magnitude of $\sigma_{ni}$. Variation of interface capture cross-sections suggests transition of defects, therefore in the case of Kr$^+$ irradiation, an approximate threshold value of fluency $10^6 \text{cm}^{-2}$ could be deduced. At fluencies higher than this value, Kr$^+$ irradiation results in the formation of high order defects. However, for a better understanding of the defect structure other analytical methods have to be used [6].
5 CONCLUSION

We described the design of a low-frequency $C-V$ curve measurement set-up by quasistatic method. The methodology of measurement was investigated and the influence of input parameters upon the results of measurement was studied on a set of structures prepared by various technologies. From the experimental data and subsequent theoretical analysis, the energy distribution of interface trap density was obtained. Thereby, the quasistatic method represents an efficient tool for quality characterization of the semiconductor-insulator interface with a significant impact upon the charge transfer in unipolar technology. We also investigated the applicability of this method to the irradiated MOS structure. The density of interface traps and their electrical activity increased markedly with the fluency and the mass of heavy ions. In regard to measurement results, the interface Si–SiO$_2$ has a crucial influence on the irradiated MOS structure quality.

It is furthermore concluded that for complex investigation of interface properties, usage of other methods (eg, $C-t$ technique) is desirable.

Acknowledgement

This work was supported by the Slovak Grant Agency project No. 1/0169/03.

REFERENCES


Received 2 February 2004

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