Study of band gap surface states of silicon in a MOSFET using surface photovoltage spectroscopy (SPS)

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Abstract. A study of band gap surface states of silicon in a MOSFET using surface photovoltage spectroscopy (SPS) is presented. The metal-oxide-semiconductor (MOS) structure inside the MOSFET was utilized in the measurements. Surface state energy positions, as well as surface state parameters that govern the charging and discharging of surface states, were determined from the surface photovoltage spectra and surface photovoltage transient plots respectively.

1. Introduction
Surface photovoltage spectroscopy (SPS) is a well established contactless technique that has been used for many years in profiling the surface of semiconductors, and thus provided relevant information about surface electronics and surface states [1-8]. Comprehensive reviews about the technique have been carried out by Kronik and Shapira [2,6] and Schroder [5]. SPS was used primarily by the group of Balestra [7,8] in the study of CdS surface electronics. With the rise of advanced semiconductor technologies, SPS found additional applications such as in plastically deformed Ge [9], determination of band offsets in heterojunction structures [10] and quantum well structures [11].

In this paper, the SPS technique was employed in the study of band gap surface states of silicon substrate in metal-oxide-semiconductor field effect transistor (MOSFET). This includes the determination of surface state energy positions and calculation of surface state transient parameters. MOSFETs are metal-oxide-semiconductor (MOS) products that have become the dominant technology in the semiconductor industry [12]. The energy band diagram of the probe-air-semiconductor (used in Kelvin probe arrangement used in SPS) is analogous to that of a MOS capacitor [5]. Thus, the MOS structure inside the MOSFET was utilized in the study of silicon substrate electronics.

2. Methodology
Surface photovoltage (SPV) is defined as an illumination-induced change in the surface potential [2,3,6]. This change is measured as the contact potential difference (CPD) between a reference electrode and the sample under consideration [2,6,7]. In the case of the MOS capacitor, the MIS approach is employed. In this method, the SPV can be found directly by measuring the photoinduced voltage change between the MIS (or MOS) capacitor terminals [2,6]. The arrangement is illuminated with modulated light intensity that produces periodic SPV.
2.1. Sample preparation
The samples used were n-channel HEXFET power MOSFETs. In order to expose the silicon substrate to be illuminated, mechanical (through grinding) and chemical processes (through dipping in a 97% H$_2$SO$_4$ solution) were performed on the samples. The silicon substrate surfaces were then etched with analytical grade HCl in order to make them free from impurities.

2.2. Surface state determination and surface state parameters calculation
In order to utilize the MOS structure inside the MOSFET, the gate (corresponding to the metal electrode) was connected to the positive terminal of the signal-picking probe while the source (corresponding to the semiconductor electrode) was grounded. The samples were illuminated with intense white light after each scan and were left in the dark for some time before another scan in order for the charges to equilibrate [7,8].

In order to obtain the surface state energy positions, changes in slope in the SPV spectra versus incident wavelength or photon energy was taken into consideration [7]. In this paper, the second derivative of the SPV spectra versus incident wavelength was used. The plot of the second derivative of the SPV spectra with respect to wavelength versus wavelength gives the position of the surface states since changes in slope implies second derivative.

Once the positions of the surface states were determined, the samples were illuminated with light energy matching the energy positions of the surface states as was done by the group of Balestra [8]. Analysis of the SPV versus time plot gives the surface state transient parameters which include the capture cross section of surface states for electrons and photons, and the density of states. Detailed mathematical treatment leading to the determination of these parameters from the transient photovoltage plot can be found in the work of the group of Balestra [8].

3. Results and Discussions
The SPV induced by light illumination is measured capacitively as potential difference between the gate and source terminals of the MOSFET. Light illumination results in a variation of the charge carriers in the surface, which in turn induce a change in the bulk charge distribution in order to satisfy the charge neutrality condition. These movements of charges produce a potential drop measurable as the CPD [6].

3.1. Surface photovoltage spectra from MOSFETs and surface states energy positions

![Figure 1. SPV spectra of HCl etched samples immediately after etching and after several hours.](image1)

![Figure 2. Plot of the second derivative of the SPV spectrum versus light wavelength.](image2)
Shown in figure 1 are the SPV spectra obtained from the MOSFET samples. The plots include SPV spectra taken immediately after etching, three hours and 24 hours after etching. It can be observed that longer exposure to darkness resulted in a better spectral response. The band gap transition is better observable in the spectra of the SPV taken after 24 hours, implying that states are better defined if samples are allowed to equilibrate for some hours. This spectrum was used in the succeeding analysis.

The positions of the surface states can be obtained by taking into consideration the changes in slope in the SPV spectrum [7]. The changes in slope can be found by taking the second derivative of the SPV spectrum. Figure 2 shows the second derivative of the SPV spectra with respect to wavelength taken after 24 hours. Shown also in the figure are the positions of the surface states. Two surface states were found, one at 1284 nm corresponding to 0.97 eV (M1) and the other at 1154 nm matching 1.08 eV (M2), both measured from the valence band. The detected band gap is 1.15 eV.

3.2. Surface states parameters from the surface state transient measurement

![Figure 3](image)

**Figure 3.** Surface photovoltage transients, with illumination at $\lambda = 1284$ nm for surface state at 0.97 eV (a), and illumination at $\lambda = 1154$ nm for surface state at 1.08 eV (b).

The surface photovoltage transient plots are shown in figure 3. The state at energy 0.97 eV showed a slower rate of SPV increase (six minutes) compared to the state at 1.08 eV (three minutes). In parallel with the discussions presented in [8], the 0.97 eV surface state is deeper compared to the 1.08 eV surface state, since deeper states take longer time to react to incident light. In other words, the 0.97 eV surface state position corresponds to slow states while the 1.08 eV surface state position corresponds to fast states.

| Position in eV | Wavelength (nm) | Intensity (photons/cm² s) | $V_s^0$ (mV) | $\delta V_s^1$ (mV) | $\dot{V}_s^0$ (mV/s) | $\dot{V}_s^1$ (mV/s) | $\ddot{V}_s$ (mV/s) |
|---------------|-----------------|--------------------------|--------------|---------------------|----------------------|---------------------|---------------------|
| 0.97          | 1284            | $1.13 \times 10^{18}$    | 43.17        | 3.92                | 0.012                | -0.0056             | -0.0065             |
| 1.08          | 1154            | $1.13 \times 10^{18}$    | 45.27        | 930.94              | 12.54                | -6.89               | -1.13               |
Table 2. Calculated values of the surface state transient measurement parameters.

| Position in eV | Density of occupied surface states, \(n^0_t\) \((\text{cm}^{-2})\) | Density of electrons trapped at the surface states, \(n^1_t\) \((\text{cm}^{-2})\) | Density of unoccupied surface states, \(p^0_t\) \((\text{cm}^{-2})\) | Capture cross section for photons, \(K_{ph}\) \((\text{cm}^2)\) | Capture cross section for electrons, \(K_n\) \((\text{cm}^3\text{s}^{-1})\) | Fractional occupancy of surface states \(f_n\) | Total density of states \(N_t\) \((\text{cm}^{-2})\) |
|---------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.97          | 1.77 x 10^{11} | 8.17 x 10^{10} | 2.61 x 10^{12} | 1.47 x 10^{-21} | 2.36 x 10^{-31} | 0.03           | 2.79 x 10^{12} |
| 1.08          | 5.03 x 10^{13} | 2.76 x 10^{13} | 1.83 x 10^{12} | 5.37 x 10^{-21} | 1.05 x 10^{-11} | 0.96           | 5.22 x 10^{13} |

Table 1 presents the pertinent quantities needed to obtain the surface state transient parameters. The calculated surface states transient parameters are presented in table 2. The values are in agreement with the results presented in [8]. The calculated surface state transient parameters are of considerable importance in dealing with the electronic and optical characteristics [8] of the silicon substrate surface. It was shown that study of silicon electronics and even its optical properties can be performed using a MOSFET device.

4. Conclusion
The important result of this paper is that the SPS study of electronic properties of surface states in silicon can be done using a MOSFET device. The calculated values for the surface state parameters are reasonable. Subsequently, MOSFET device parameters characterization involving the effect of surface states can be performed by employing the MOS structure in it. The use of the MOS structure in this study yielded valuable information on the electronic properties of the silicon surface.

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