High resolution impedance and potential imaging

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Background

Photocurrent measurements at field-effect structures such as electrolyte-insulator-semiconductor or metal-insulator-semiconductor structures have been used to measure local electrical potentials, local concentrations such as pH or hydrogen gas and the local impedance of thin films (Figure 1) [1,2]. Local concentration and potential measurements are known as Light Addressable Potentiometric Sensors while local impedance measurements are carried out using Scanning Photo-induced Impedance Microscopy. In both techniques electron-hole pairs are generated by a laser focused into the space charge region of the semiconductor. If the field-effect structure is biased towards depletion or inversion the photo-generated charge carriers separate in the field of the space charge region causing a current to flow. Modulation of the laser beam intensity results in an ac-photocurrent. As the current is limited to the illuminated area of the structure measurement can be carried out with spatial resolution.

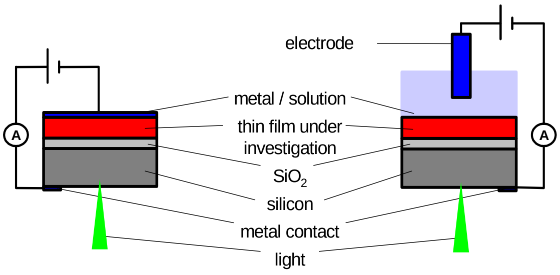

Figure 1. Field-effect structures used for local impedance and potential measurements.

The dependence of the photocurrent on the dc voltage applied is shown in Figure 2. With increasing depletion an increase in the photocurrent is observed reaching a plateau when the structure is biased towards inversion. A shift of the photocurrent curve along the voltage axis indicates a change in the local potential; a change in the maximum photocurrent can be translated into a change in the local impedance of materials deposited onto the insulator. This technique has potential applications in the characterization of heterogeneous materials or the local electrical properties of living cells or biological membranes.

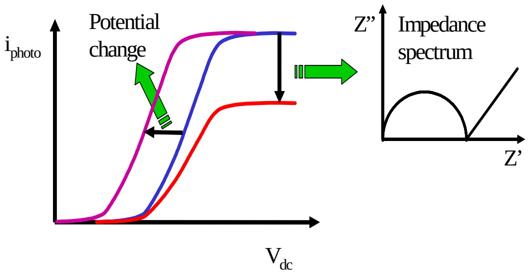

Figure 2. Changes in the maximum photocurrent and the position of the photocurrent curve on the dc voltage axis can be used to measure local impedance or electrical potentials.

Lateral resolution of photocurrent measurements

The lateral resolution of photocurrent measurements is determined by the properties of the semiconductor substrate, the quality of the focus of light and the wavelength employed. Charge carriers generated in the bulk of the semiconductor substrate do not only diffuse to the space charge layer where they cause a current but they also diffuse laterally resulting in a loss of resolution. Recent experiments have shown that the lateral diffusion length of charge carriers can be reduced to less than one micrometer by using a thin epitaxial layer of silicon on a sapphire substrate (SOS) or a semiconductor with a short diffusion length of charge carriers such as amorphous silicon [3]. However in both cases the low quality of the insulator limits the application of these semiconductor substrates. In the case of amorphous silicon low temperature silicon dioxide had to be deposited resulting in a large number of interface states; in the case of SOS a large number of interface states and defects in the oxide were obtained due to the mechanical tensions in the material during oxide growth caused by the mismatch in thermal expansion coefficients of sapphire and silicon.

To avoid the problems encountered using thin silicon layers and amorphous silicon, it would be advantageous if bulk silicon could be employed. However, if a laser beam is focused into the space charge region from the back of the semiconductor substrate, light has to travel through the bulk of the material where it generates charge carriers resulting in a loss of resolution (Figure 3). If light with energy smaller than the bandgap is used, no charge carriers are generated in the bulk of the semiconductor. Electron-hole pairs are generated only in the focus near the space charge layer at the semiconductor/insulator interface due to the optical non linearity of two-photon absorption. The possibility of high- resolution SPIM/LAPS measurements using a two-photon effect in bulk silicon was investigated in this project.

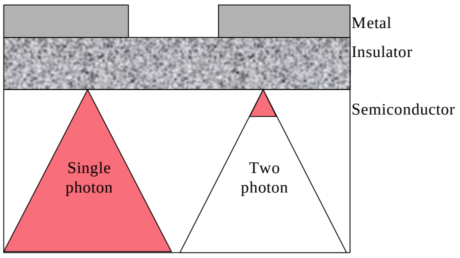

Figure 3. In case of a single photon effect charge carriers are produced throughout the bulk of the material. In case of a two photon effect charge carrier generation is confined to the focus near the space charge region of the semiconductor.

Experimental

Sample preparation: Double polished p-type silicon with a 40 nm thick thermally grown layer of silicon dioxide was used as the semiconductor substrate for photocurrent measurements. Some 100 nm of aluminium were deposited onto the back of the silicon substrate after etching with 10% HF. An ohmic contact was established by heating the samples to 350°C for 5 min on a hotplate. Patterns were generated by printing cellulose acetate from a 10 % solution in ethyl lactate onto the silicon dioxide using a high-resolution electrospray printing technique described by S.N. Jayasinghe *et al.*[4].

Experimental setup: Femtosecond pulses at a wavelength of 1250 nm were produced using a titanium-sapphire laser operated at a frequency of 76 MHz in conjunction with an optical parametric oscillator. Residual lower wavelengths generated by the Argon ion pump laser and the Ti-sapphire laser were filtered out using an appropriate filter. The light was chopped at a frequency of 1 kHz and focused into the space-charge region of the silicon using a Nikon (CFI plan fluor x20, wd 1mm, na 0.75) microscope objective. A PI XYZ positioning system and an EG&G 7260 lock-in amplifier were incorporated into the setup to move the sample with respect to the laser beam and carry out photocurrent measurements.

Results

To demonstrate that a two photon effect was obtained, the intensity dependence of the photocurrent was measured using the femtosecond laser at 1250 nm and a He-Ne Laser at 632 nm, the latter of which produced an ordinary single photon effect. The double logarithmic plot of photocurrent versus intensity shows a linear relationship in both cases (Figure 4). A slope close to 1 was obtained for the He-Ne laser indicating a linear relationship between current and intensity as expected for a single photon experiment. In case of the longer wavelength, a slope of 1.94 was obtained confirming that the photocurrent increased quadratically with the intensity as expected for a two photon experiment. Experiments previously carried out at 1560 nm showed that a further increase in the wavelength only resulted in a marginal increase in the slope.

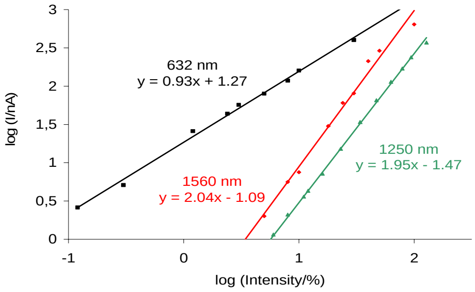

Figure 4. Intensity dependence of the photocurrent at three different wavelengths.

An image of a cellulose acetate cross (line width 80 μm) printed onto a silicon/silicon dioxide substrate and the corresponding photocurrent curves are shown in Figures 5 and 6. The shift of the photocurrent curves along the voltage axis by several hundred millivolts on the printed lines (C) and their surrounding area (B) indicates strong charging of the silicon dioxide caused by the electrospray printing process. Interestingly, the shift is slightly reduced in the polymer coated area of the sample.

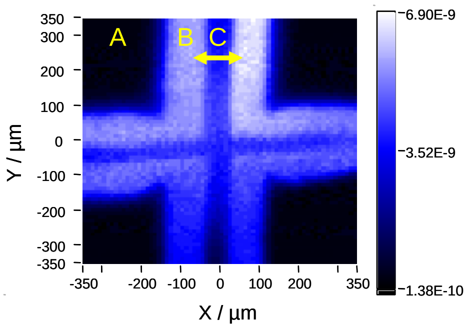

Figure 5. Photocurrent image of cellulose acetate lines printed by electrospray. Image recorded at V_{dc} = 0.5 V.

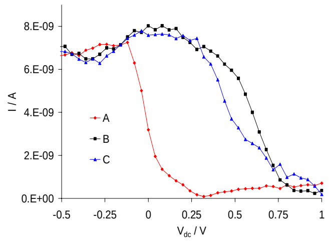

Figure 6. Photocurrent-voltage curves measured in positions A,B and C indicated in Figure 5.

A resolution about 16 μm was estimated from detailed photocurrent line scans across the cellulose acetate pattern (Figure 7). The resolution commonly achieved using bulk silicon with a laser focused from the back of the substrate is several hundred micrometers. Even though an improvement by more than a factor of ten was achieved, the results were not as good as expected. The reasons for this could be as follows: 1. The focus through a 400 μm thick silicon substrate was not very good, and a significant number of electron-hole pairs were generated outside the space charge layer resulting in lateral diffusion of charge carriers; 2. The distribution of charge carriers in the silicon dioxide caused by the printing process is unknown. This could lead to a distorted line scan; 3. As different areas on the sample carry different charges, there could be significant crosstalk between them causing a loss in resolution.

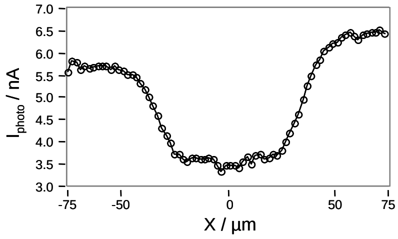

Figure 7. Line scan across cellulose acetate line (indicated by arrow in Figure 5).

Outlook

An improvement of the focus inside the silicon substrate could be achieved using solid immersion lenses in conjunction with a two-photon effect. Ramsay *et al.* reported a resolution of 325 nm for subsurface imaging of a silicon flip chip using a wavelength of 1530 nm and high-numerical-aperture solid immersion lenses[5]. Model system for SPIM measurements will in the future be generated using lithographic or printing techniques that do not cause charging. A suitable model system for LAPS should measure local potential changes rather than stationary charges to avoid the effect of crosstalk.

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