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A STUDY OF BACKSIDE LASER-PROBE SIGNALS IN MOSFETS

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ABSTRACT

The performance of a laser-probing system due to analyzing signals in MOSFETs is studied. A heterodyne laser interferometer is used for the detection of changes in the free carrier concentrations induced by terminal biases in n-channel and p-channel MOSFETs. Measurements of the phase shift and intensity changes are carried out in accumulation, inversion and depletion and compared to the results of a rigorous numerical modeling of the wave propagation. In the depletion region, the effect of the standing wave resulting from the reflection from the gate is observed in experiment. As the sensitivity of the phase shift measurements is in the order of 10^{-5} rad, doping profiles could be derived from optical experiment. We found that a strong impact of the reflection properties of the polysilicon gate on the intensity signal poses a restriction to the applicability of the intensity modulation measurements for the inversion and accumulation conditions.

1. INTRODUCTION

In the recent years, due to an increasing demand on the quality and reliability of integrated circuits, on-wafer testing has become immensely important. The steadily growing complexity and the implementation of improved packaging methods (Lead on Chip Frame, Flip Chip Bonding) require the development of new testing sites. Presently there are great efforts in establishing optical techniques for on-chip testing. Indirect optical methods [1,2] detect the change of the electrooptic properties of a prober (e.g. the birefringence in crystals) due to device operation. Other methods get information from the device under test (DUT), as local heating and local changes of the free carrier concentrations directly influence the refraction index of the semiconductor material [3-6]. A different approach represents the detection of recombination radiation in power devices [7] as a mean to extract transient carrier profiles in Gate-Turn-Off (GTO) thyristors [8,9]. So far, several qualitative studies of optical methods have been published. In the following we present some quantitative results for a backside laser-probe set-up developed by Goldstein et al. [10] applied to conventional bulk MOSFETs.

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2. EXPERIMENTAL TECHNIQUE

The measurement set-up for our experiments (Figure 1) is similar to that proposed in [10] where the laser diode operates in pulsed mode.

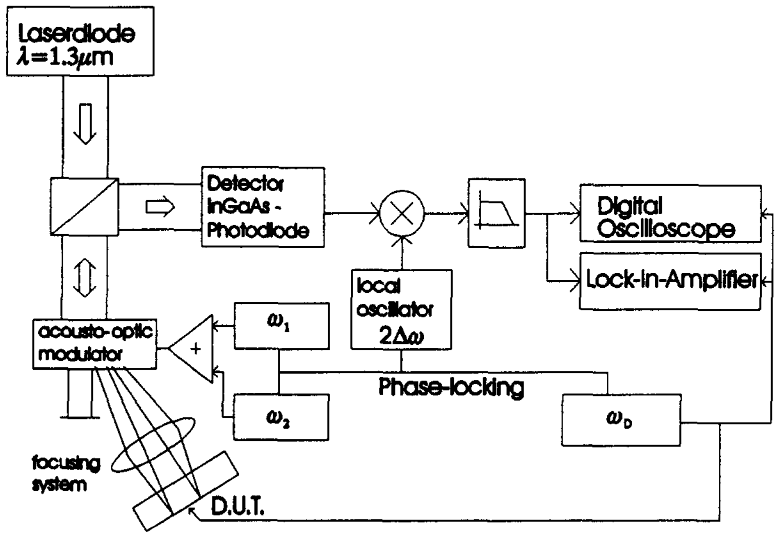

Figure 1: Measurement set-up for testing MOSFETs through the substrate-side. The acousto-optic modulator is driven by ω_1 and ω_2. The pulses applied to MOSFETs have a repetition rate of T, with $\omega_D=2\pi/T$. The local oscillator is set to $2\Delta\omega$ ($\Delta\omega=\omega_1-\omega_2$).

In our system the laser operates in CW-mode, which enables that the test MOSFETs can be driven at low frequencies (in the range of 10^2 to 10^3 Hz). Phase and intensity changes of a probing beam (focused at the center of the channel) with respect to a reference beam (positioned outside the channel) are interferometrically detected. In the detected power spectrum the phase and intensity modulations cause sidebands around $2\Delta\omega$ ($\Delta\omega=\omega_1-\omega_2$). These sidebands are mixed to the baseband, where the phase of the local oscillator with respect to the carrier $2\Delta\omega$ determines whether the phase or the intensity modulation is detected. Timing signals are obtained after lowpass filtering and sufficient averaging by a digital oscilloscope. The values of the relative phase shift and intensity changes are measured by a lock-in amplifier. In all the experiments carried out on MOSFETs the signals applied to the gate are trapezoidal pulses with different width and repetition rate. The pulse low level is set to the flatband, the pulse high level is varied. The source and drain junctions are grounded and therefore, there is no local heating in the device during measurement.

3. NUMERICAL MODELING OF THE LASER-BEAM MODULATION

The phase and intensity modulation of the probing beam due to local changes in the complex refractive index induced by gate pulses are numerically modelled. The model [11] is derived from the transmission line theory. The distributions of the electron and hole concentrations in MOSFETs at different gate biases are obtained by employing MINIMOS-6 simulation. The local perturbations Δn_j and κ_j of the refractive index are then calculated for the classical Drude model [12] and the Drude model fitted to experimental (non-linear) data from [12,13]. This gives constant values of the complex index of refraction $n_j = n_0 + \Delta n_j - i\kappa_j$ across particular discretization segments along the beam path (y-coordinates $\Delta y_1 \ldots \Delta y_{ny}$) chosen in the center of the channel perpendicular to the gate, resulting in discrete wave-impedances

$$\overline{Z}_{w,j} = \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0}} \cdot \frac{1}{\overline{n_j}}, \quad j = 1 \ldots ny \ . \tag{1}$$

The impedance seen from the following discretization layer is

$$\overline{Z}_{c,j} = \overline{Z}_{w,j} \cdot \frac{\overline{Z}_{c,j-1} + \overline{Z}_{w,j} \cdot \tanh(\overline{\gamma_j} \Delta y_j)}{\overline{Z}_{w,j} + \overline{Z}_{c,j-1} \cdot \tanh(\overline{\gamma_j} \Delta y_j)}, \tag{2}$$

with the wave number of the layer

$$\overline{\gamma_j} = \frac{2\pi}{\lambda} \cdot \left(\kappa_j + i \cdot \left(n_0 + \Delta n_j\right)\right) . \tag{3}$$

The relative phase and intensity changes are calculated from the modulus and the phase of the complex reflection coefficient $\overline{\rho}$ for a plane electromagnetic wave propagating through the nonuniformly doped substrate,

$$\overline{\rho} = \frac{\overline{Z_C} - \overline{Z_W}}{\overline{Z_C} + \overline{Z_W}} \ . \tag{4}$$

$\overline{Z_W}$ is the wave impedance of the unperturbed bulk silicon and $\overline{Z_C}$ is the total characteristic impedance seen from the bottom of the simulation area ($y_{ny} \approx 1\mu m$). In addition a geometric-optic approach [14] is used for a rough estimation of the phase and intensity changes.

The calculations are performed for n- and p-channel MOSFETs with 20µm gate length and 20µm gate width. The doping profiles in the channel region and the oxide thickness are extracted from the split C-V measurements, carefully applied near the flatband (close to the interface) and with the polarized junctions (in order to penetrate deeper into the bulk), Figure 2. The calculated gate capacitance (junction-overlap and side-wall contributions excluded) agrees well with the measured gate-bulk capacitance in the depletion region (Figure 3), which confirms the accuracy of the doping profiles used in beam-modulation modeling.

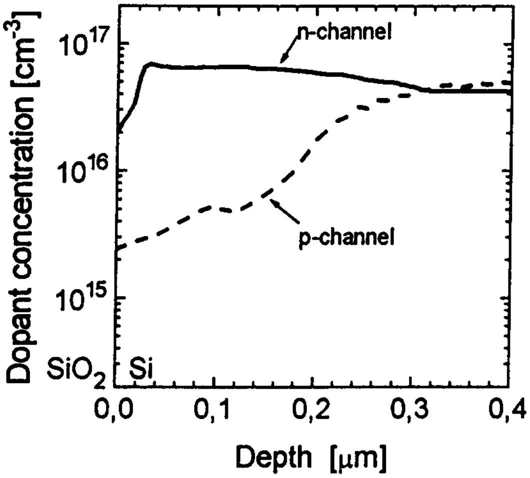

Figure 2: Extracted doping profiles in the channel region in the analyzed MOSFETs.

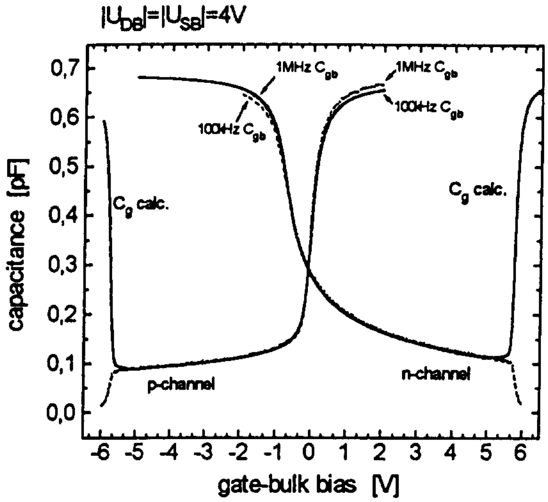

Figure 3: The gate capacitance calculated with MINIMOS-6 compared with the measured gate-bulk capacitance confirms the accuracy of the profiles (Figure 2) used in modeling.

4. EXPERIMENTAL AND MODELING RESULTS

Numerical results for the intensity change in p-channel devices (Figure 4) show a

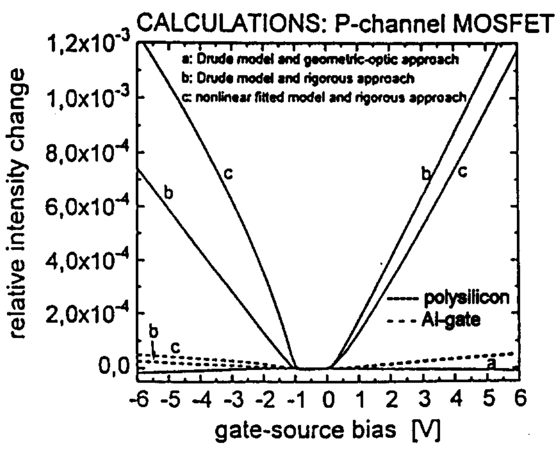

Figure 4: Numerical results for the intensity change in p-MOSFETs driven in inversion, depletion and accumulation.

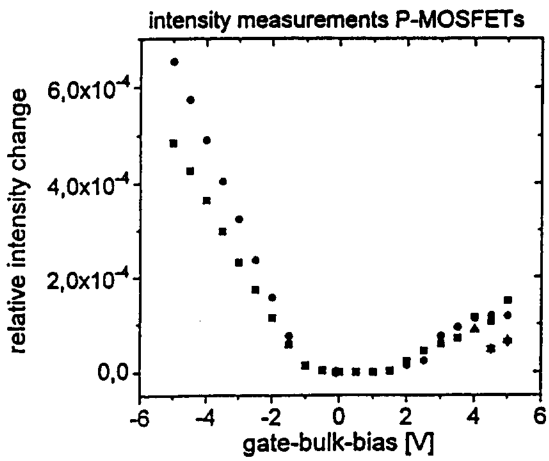

Figure 5: Intensity shift measured in p- MOSFETs.

great impact of the type of reflector (polysilicon or Al gate) on the intensity signal. Measured values (Figure 5) of the intensity change coincide with the calculated data on the inversion side, but they are smaller than calculated values on the accumulation side. Timing signals of the intensity modulation obtained after filtering the noisy detector signal by a digital oscilloscope are shown in Figure 6.

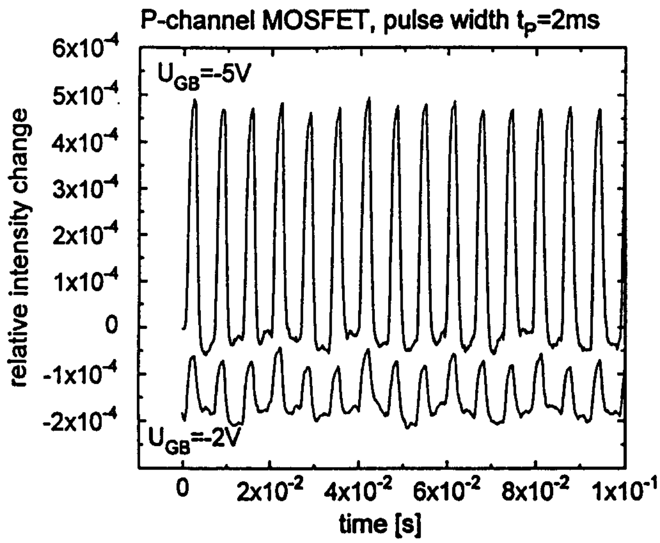

Figure 6: Oscilloscoped intensity signals in MOSFETs (pulse width 2ms, duty cycle 13%).

Since typical values of 1-2 nm for the (quantum-mechanical) inversion layer thickness are much smaller than the optical wavelength in silicon in our experiments of 371 nm, the interaction between the laser beam and the substrate strongly depends on the standing wave pattern due to reflection on the gate. In depletion, however, the thickness of the modulatory layer can be in the order of the laser wavelength. Figures 7 and 8 show the results of numerical calculations for the phase and intensity modulation in n-channel devices, respectively.

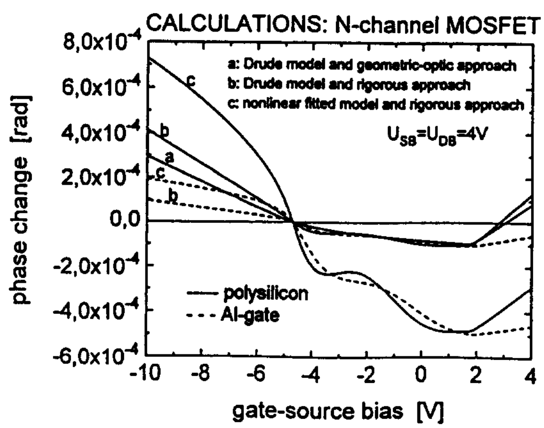

Figure 7: Calculations of phase shifts in depletion (n-MOSFETs).

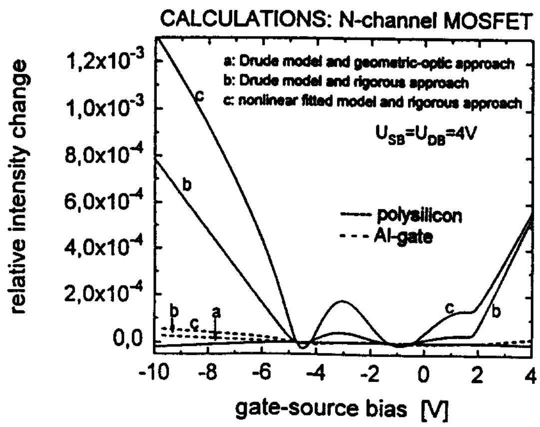

Figure 8: Calculations of the intensity change in depletion (n-MOSFETs).

By increasing the applied gate voltage in the subthreshold region from the flatband to the device threshold voltage the width of the modulatory region increases. Note that the depletion region under the gate can significantly be extended by reversely biasing the bulk-drain and bulk-source junctions, as applied in our experiments. In Figures 7 and 8 the first maximum of the standing wave can be observed, occurring at gate-bias of -3V. The effects occurring in the depletion region are clarified by studying an ideal case where the doping level in the bulk is assumed constant (10^{16} cm^{-3}), but the width of the depleted layer is varied. The calculated results for that ideal case are shown in Figure 9.

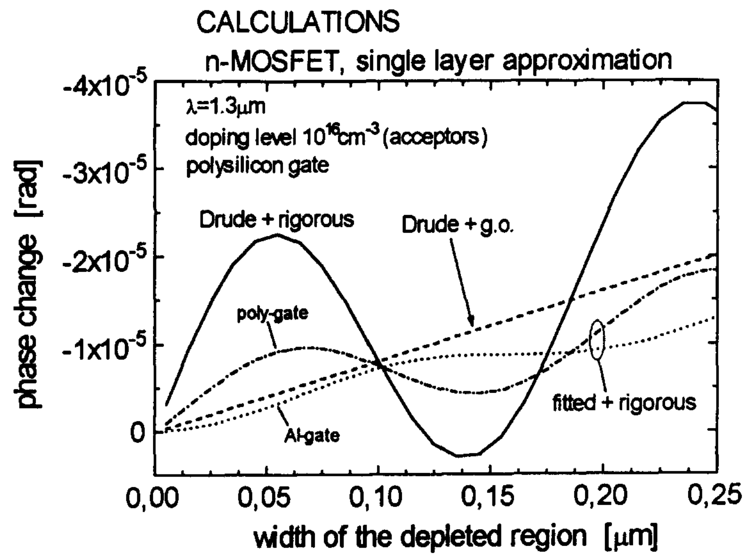

Figure 9: Single-layer approach for calculating the phase shift in the n-MOSFETs used in experiments, under the assumption of uniform bulk doping. The width of the modulatory region is increased in experiment by applying positive gate voltages up to the threshold voltage.

There is a certain sensitivity of the phase signal to the gate material, but less as for the case of intensity measurements. Numerical results in depletion for the p-MOSFETs used in our experiments provide changes in the phase in the order of 10^{-6} rad, which are not detectable by the present interferometer set-up. For n-channel MOSFETs, however, we get in depletion the signals drawn in Figures 10 and 11 for phase and intensity variations, respectively. The standing wave nature is obvious although the experimental results are opposite in sign for the phase experiments.

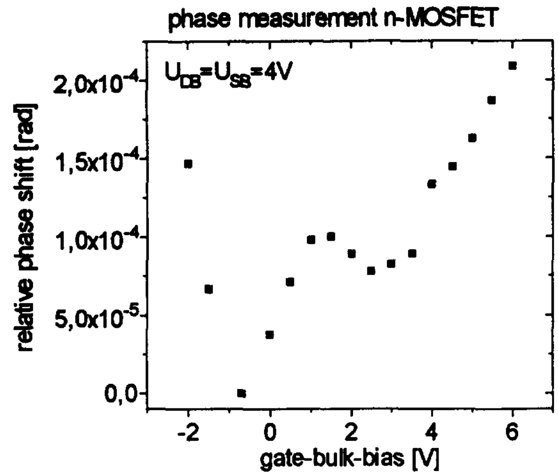

Figure 10: Phase shift in n-MOSFETs obtained in experiment as a function of the depletion width. The bulk is polarized

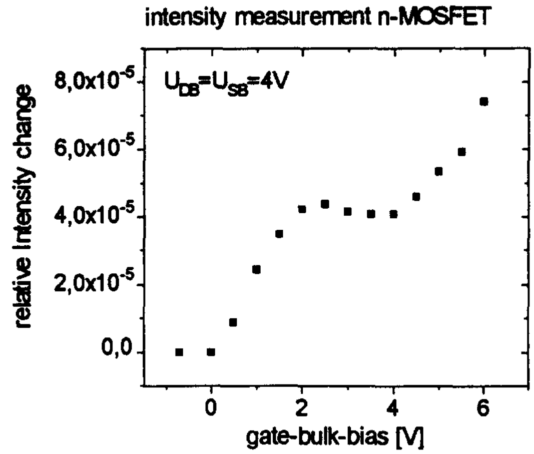

Figure 11: Experimental results for intensity measurements in n-MOSFETs. The bulk is polarized.

5. DISCUSSION

Probing intensity signals in MOSFETs from the substrate side can provide reliable results in accumulation and inversion when the exact gate conductivity near the gate/SiO_2-interface is known. The developed numerical model for the wave propagation in the bulk describes well the modulation of the phase of the probing beam [11]. There is still not a good reproducibility of the phase and intensity changes between different experiments. This problem may be attributed to an imperfect focusing of the beams on the probe due to fluctuations in the immersion oil of the objective lens. Since the present model only considers waves propagating with normal incidence, numerical analysis does not account for waves contributing to the detected signal with oblique incidence. Measuring in depletion may be a good candidate for optical determination of the bulk doping level. From numerical simulations we expect a negative shift in the phase in depletion which has not been observed in experiments where the phase shift (relative to the flatband conditions) is always positive. We have found a small impact of the probing beam on the I-V characteristic in subthreshold region, changing the optical properties of the bulk at large laser intensities. In addition, photon-assisted tunnelling (Franz-Keldysh-effect), which has not been considered in the present numerical modeling, may also have influence on the absorption properties due to very high perpendicular fields in silicon close to the interface in MOSFETs.

6. CONCLUSIONS

We have presented measurement and calculation results for a backside laser probing technique. This testing method has been studied for its applicability in analyzing free carrier concentrations in MOSFETs. Compared to a rigorous numerical model, the measured phase and intensity shifts are in the expected range, but strongly depend on the gate resistivity. The standing wave nature in depletion has been observed in experiment giving a different sign of the phase signal compared to the results of the numerical calculations. We have shown that bulk doping profiles could be extracted from experiments for the concentration levels higher than about 10^{16} cm^{-3}. Further studies of the backside laser probing method should consider thermal effects as well as electric field effects in various MOS devices.

7. ACKNOWLEDGEMENTS

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