Combined electrical and optical heating in thermal wave microscopy of semiconductor devices

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Insulating lines and channels implanted by focused ion beams on SIMOX wafers have been investigated by thermal reflectance microscopy using optical and electrical excitation. In addition optical beam induced current (OBIC) has been measured from the same structures. A very poor contrast in thermo-reflectance was observed with modulated optical pump only, whereas hot lines and hot spots can be visualized by modulated electrical heating. Insulating lines forming channels can only be imaged with simultaneous optical and electrical excitation. Best contrast for the observation of the insulating lines adjacent to a channel are achieved by recording the reflectance signal at 4f where f is the modulation frequency of the optical and electrical pump. The results of the OBIC measurements point towards a thermal origin of the double excited thermo-reflectance signal.

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Introduction
Over the last twenty years thermo-reflectance microscopy of thermal waves has become a very versatile and powerful tool for the analysis of semiconductor materials and devices. It offers a relatively good spatial resolution in a completely non-contact way. Using either optical excitation or electrical heating one can obtain information about thermal and electronic properties [1] or temperature distributions (e. g. hot spots) [2]. Here we want to show that the combination of the optical and electrical excitation mechanisms can reveal further information, that cannot be achieved by only using a single form of modulated heating. We also make use of the optical beam induced current (OBIC) measurements as a complementary microscopic method to get insight into the origin of the contrast enhancement.

Experimental
The experiments are conducted with a thermo-reflectance arrangement using a HeNe-laser as probe. The local heating was achieved by either a focused modulated Ar-ion laser beam and/or electrically by connecting the device to an DC- or AC-power supply. The samples were SIMOX-wafers which have been structured by ion beams. The mesa consists of 500 µm Si substrate with a 380 nm SiO₂ layer on it and a p-Si layer of 150 nm thickness on the top. Insulating lines with widths of 100 nm were written with a focused Ga-beam of a commercial system. Lines of P and B implantations with widths of 4 µm were produced with the micro-beam facility at the Tandem accelerator laboratory of the Ruhr-University of Bochum. Here we report on results obtained from one FIB and one µ-beam structured mesa.

Results
a) Insulating line written with µ-beam
Spatially resolved thermoreflectance measurements with optical excitation showed only very little or no contrast between the substrate and the implanted lines (Fig.1, U = 0V). This may be due to the layered structure of the substrate. From frequency dependent thermoreflectance measurements it can be seen that the signal is dominated by the thermal wave, which is only negligibly affected by the implantation. However, the contrast between the substrate and the implanted lines can be enhanced by applying an additional electrical voltage across the implanted lines (Fig.1, bottom). Instead of a DC voltage an AC voltage can also be used. In this case one has to detect at higher harmonics of the excitation frequencies and signal only from the insulating lines is obtained. When dealing with continuous insulating lines, it is also possible to work with pure electrical heating at high voltages, but this method fails when applied on insulating lines with small channels as in the case of the second sample, which was produced on the same mesa but now using a focused ion beam of about 100 nm width.

b) Insulating line with channel written with a Focused Ion Beam (FIB)
Like in the first sample described before, the insulating lines cannot be seen in the second sample by a thermo-reflectance measurement with optical heating only. Switching off the optical heating and switching on an electrical heating with an AC-voltage across the insulating line a hot spot located in the channel can be observed (Fig.2). This spot corresponds to spots detected by the thermo-elastic microscope in in-plane-gate transistors [3]. The variations of the signal with modulation frequency and with the electrical power are in agreement with a
Fig. 1: a) Insulating lines written by µ-beam into SIMOX-wafer. The horizontal line shows the scan direction of the probe beam. b) Thermo-reflectance signal due to modulated optical heating with an additional DC-voltage between source and gate.

thermal origin of the signal. However, the implanted insulating lines forming the channel cannot be observed with neither optical heating alone or electrical heating alone. Only the combination of both heating mechanisms allows the detection of the buried lines.

Combination of optical and electrical heating can be effected in different ways. Running the thermo-reflectance experiment with a modulated pump laser beam the additional electrical excitation could be a DC- or and AC-voltage across the line. In the case of a modulated electrical heating a DC optical excitation can be applied additionally. All three types of combinations finally lead to an observation of the buried lines. However, the contrast and the ratio of intensity of the hot spot and buried line vary considerably.

When imaging the device with the modulated optical pump beam an additional DC-voltage U across the lines leads to an increase of the intensity at the position of the lines of about 20 per cent for U = 8 V.

The most pronounced effects are achieved, when both the electrical and the optical excitations are modulated at the same frequency f and the response is detected at the fourth harmonic 4f. Fig. 2 shows the amplitude image obtained at 4f where both
the channel and the buried FIB lines are appearing with about the same intensity. Also the phase image clearly displays the insulating lines, the contrast of channel, however, is lower than for the amplitude.

**Optical beam induced current (OBIC) measurements**

The observed contrast enhancement achieved with the simultaneous application of optical and electrical excitations has to be correlated with the behavior of the photo induced carriers in the electrical field across the device. In order to elucidate details of these mechanisms the thermo-reflectance images have been investigated as a function of adjustable parameters such as modulation frequency, optical and electrical power. A problem difficult to solve, however, is the separation of the thermal and electrical contributions to the thermo-reflectance signal. Therefore we have setup an additional experiment to measure the current induced locally in the device by the focused optical beam. The experimental setup for the OBIC measurements requires only a slight modification of the arrangement used for thermo-reflectance measurements. Instead of applying a voltage the optical induced current through the device is detected. Fig. 3 shows schematically the setup used in the present experiments. Excitation was effected with the HeNe-laser of 5 mW which was focused down to a spot of about 5 µm diameter. At a modulation frequency of 200 Hz and a voltage of 8 V the maximum laser beam induced current was a few µA. Laterally resolved OBIC measurements have been performed on the samples with insulating lines with and without channel as a function of the applied voltage. The amplitude and the phase scans obtained from a closed line are displayed in Fig. 4. When imaging the sample with the channel only a feature corresponding to the hot spot in Fig. 2b is observed.

The OBIC images are of purely electronic origin. There are two mechanisms which lead to a change of the current [4]. At first, the optical excited electron and hole pairs will increase the number of carriers. Their contributions is largest in the region of the potential changes where the electron and hole are separated in the potential gradient. In the other regions the pairs can recombine very fast without contributing to the current.

The second and main contribution results from the modification of the potential itself by the optically induced carriers. The reduction of the potential barrier increases the current. The FIB line acts as a npn junction. The voltage across the junction reduces the depletion region at one side and increases it on the other. The photoinduced holes are collected in p-doped region reducing the barrier height. As the mobility of the electrons is larger the electrons will travel much faster to the positive side than the holes to the negative side leading to the observed variation of the phase signal across the line.

With regard to the OBIC results the modifications of the thermal reflection signal due to double excitation is attributed to the supplementary heat production by the photoinduced increase of the current. This interpretation is supported by the fact that the phase of the thermo-reflectance signal does not change within the experimental uncertainty. The analysis of the mechanisms which lead to the enhancement at higher harmonics as compared to the DC-experiments are still in progress.

**Conclusions**

Buried insulating lines in semiconductor devices which are not accessible to thermo-reflectance microscopy working with optical or electrical heating only can be visualized by double excitation. Detection at higher harmonics yield improved contrast which most probably arises from a nonlinear interaction of both mechanisms.

**References**


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