Paper

Photoelectric measurements of the local values of the effective contact potential difference in the MOS structure

Andrzej Kudła, Henryk Przewłocki, Danuta Brzezińska, and Lech Borowicz

Abstract—We have shown that using focused UV laser beam in photoelectric methods it is possible to measure local ϕ_{MS} values over the gate area of a single MOS structure. The ϕ_{MS} distribution is such that its values are highest far away from the gate edges regions, lower in the vicinity of gate edges and still lower in the vicinity of gate corners. Examples of measurement results and description of the measurement system are presented. The dependence of the ϕ_{MS} value on the exposure time and the power density of UV light is discussed.

***Keywords—** MIS structure, photoelectrical methods, internal photoemission, contact potential difference.*

1. Introduction

It is known that mechanical stress in the metal-oxide-semiconductor (MOS) system affects its electrical parameters (e.g., [1, 2]), and that its distribution under the gate of a MOS structure is not uniform [2–4]. Therefore one can expect that local values of MOS parameters in the vicinity of gate edges and are different from those measured far away from the edge. These expectations are confirmed by measurement results showing that the values of both effective contact potential difference (ECPD) [5], referred to as the ϕ_{MS} factor, and flat band voltage V_{FB} depend on the perimeter-to-area ratio.

2. Theory

The contact potential difference in a metal-insulator-semiconductor (MIS) structure is defined by the following formula:

$$\phi_{MS} \overset{def}{=} \phi_M - \left(X + \frac{E_G}{2q} + \phi_F \right), \tag{1}$$

where ϕ_M is the potential barrier height for internal photoemission from metal to dielectric, X is the electron affinity at the semiconductor – dielectric interface, E_G is the band gap energy, q is the electron charge and ϕ_F is the Fermi level in the semiconductor.

The gate voltage V_G is divided between the individual regions of the MIS structure according to:

$$V_G = V_I + \phi_S + \phi_{MS}, \tag{2}$$

where V_I is the voltage drop across the dielectric and ϕ_S is the surface potential in the semiconductor.

The voltage V_G^0 corresponding to null photocurrent may be precisely determined using the photoelectric method [5]. When V_G^0 is applied to the gate V_I is close to zero if the diffusion photocurrents from the substrate and gate are equal. Usually ϕ_S may be calculated from CV characteristics; however, if the substrate is highly doped, the surface potential is close to zero, and V_G^0 is equal to ϕ_{MS}.

3. Measurement setup

Traditionally a xenon lamp with monochromator is used as the source of UV radiation. In such conditions it is difficult to exceed 1 mW at $\lambda = 244$ nm, simultaneously keeping the spot diameter below 1 mm and the band pass below 5 nm. Application of a laser as a UV source in photoelectric measurements of MIS structures has opened new possibilities. With UV power $P = 100$ mW at $\lambda = 244$ nm it is possible to measure samples with gates exhibiting higher absorption (thicker or made of materials with higher extinction coefficient). Moreover, it is possible to focus UV light better and measure local internal photoemission. However, higher power densities create numerous phenomena that have to be taken into account, such as electron trapping in insulator or photoemission from the semiconductor conduction band.

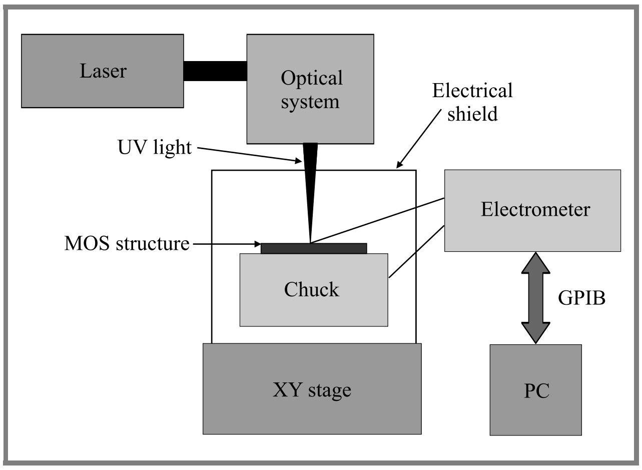

Fig. 1. Block diagram of the system for laser-based photoelectric measurements.

A system for local ϕ_{MS} photoelectrical measurement is shown in Fig. 1. In this system argon laser with a frequency doubler is used as a high-intensity UV-radiation source.

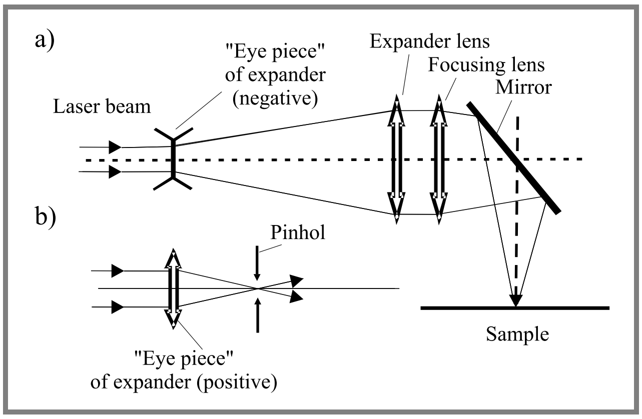

Fig. 2. Diagram of the optical subsystem: (a) with expander, Galileo configuration; (b) eye piece of the Kepler configuration with space filter.

To obtain a low diameter of the light spot a special optical subsystem has to be used (Fig. 2). One simple solution is the Galileo configuration that enables allows the spot diameter to remain in the range of 20 μm. The Kepler configuration reduces the spot diameter below 1 μm.

4. Experimental

Samples containing Al-SiO$_2$-Si MOS structures were investigated. Highly doped n-type wafers with the orientation of (100) were used. The oxide thickness t_{ox} was 60 nm, while the aluminum gate thickness t_{Al} was either 35 nm or 400 nm.

Argon ion laser with a frequency doubler was used as a UV-radiation source with the wavelength of 244 nm. The UV light spot diameter was 20–40 μm. The power of the UV beam at laser output was adjustable up to 100 mW.

5. Results

Lateral distribution of the ϕ_{MS} on MOS structure can be measured using high intensity, focused laser light (Fig. 3). It was found that the ϕ_{MS} values were the highest far away from the gate-edge regions (e.g., in the middle of a square gate), lower in the vicinity of gate edges, and still lower in the vicinity of gate corners. This result observed directly in photoelectric measurements was confirmed indirectly by purely electrical measurements.

The values of the parameters depend also on the structure dimensions (Fig. 4).

The dependence of the ϕ_{MS} on the structure size supports the assumption pointing mechanical stresses as the origin of the ϕ_{MS} changes. At higher light-power densities electron trapping in SiO$_2$ and emission from the conduction band in the semiconductor should be considered.

The influence of UV power on V_G^0 is visible in Fig. 5. With higher UV power V_G^0 increases. This could be the effect of photoemission from the silicon conduction band, which decreases electron affinity X (see formula (1)). Other important phenomena are charge trapping in the SiO$_2$ layer, resulting in V_G^0 increase, and resistance changes during measurements shown in Fig. 6.

Since the photocurrent decreased with increasing V_G^0 during the measurements illustrated in Fig. 6, it is reasonable to assume that ϕ_M has increased because electrons were trapped near the Al-SiO$_2$ interface. Electron trapping caused by UV radiation is a local property and it has

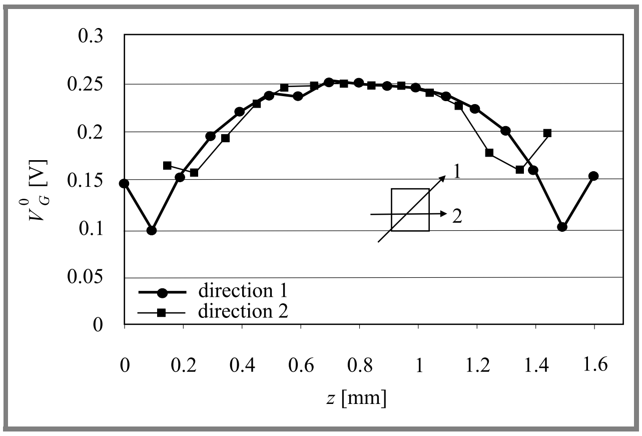

Fig. 3. The local V_G^0 values measured along two directions on a single MOS structure with a square gate.

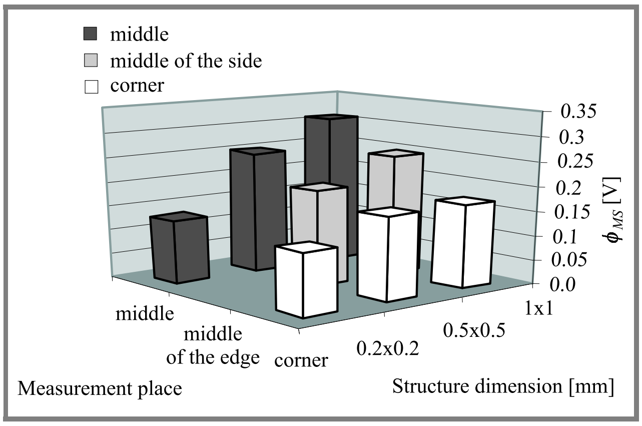

Fig. 4. The ϕ_{MS} values measured on different-size structures (fabricated on the same wafer) at the structure center, at the center of one side and in the corner.

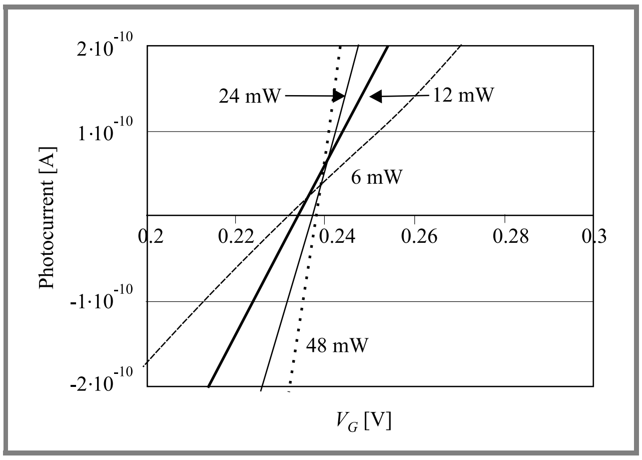

Fig. 5. *I-V* characteristics measured on a structure with $t_{\mathrm{Al}} =$ 35 nm with UV power as a parameter.

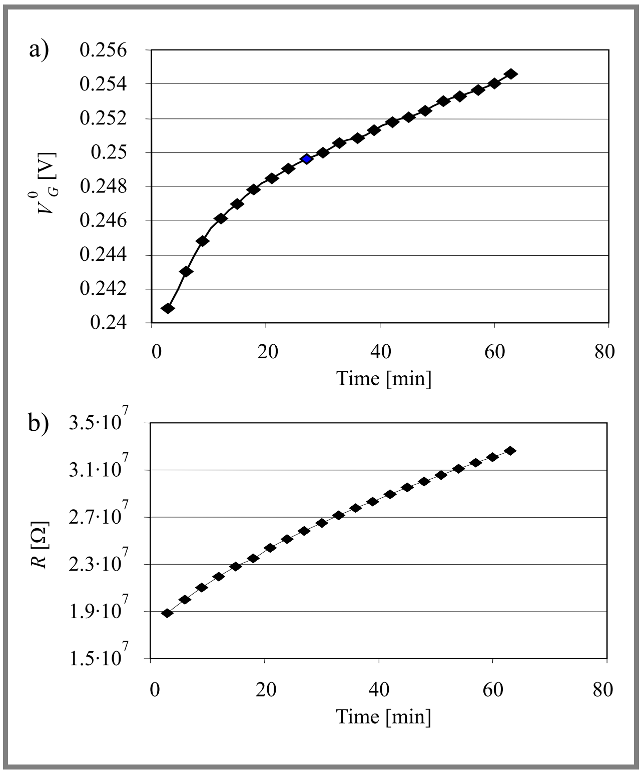

Fig. 6. Changes of the electrical properties of a MOS structure (t_{Al} = 400 nm) during long photoelectric measurements (UV power= 30 mW): (a) V_G^0 voltage and (b) structure resistivity.

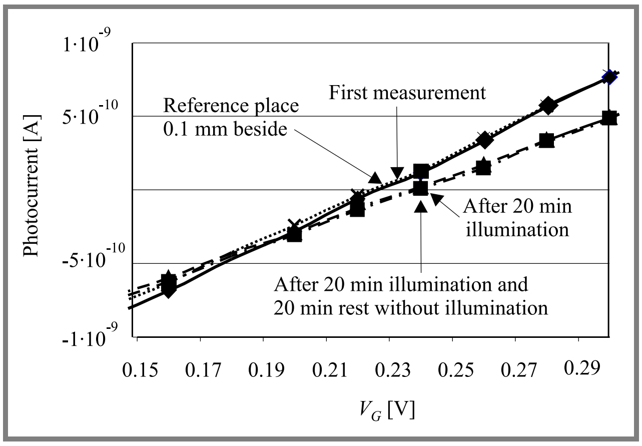

Fig. 7. *I-V* characteristics of a MOS structure with $t_{\mathrm{Al}} = 35$ nm measured before and after 20 min illumination at $P = 6$ mW and compared with the measurements taken in the same place after a 20 min period without illumination and in the reference place (its distance from the test place is 0.1 mm).

a lasting effect on the *I-V* characteristics, as shown in Fig. 7. With the light spot diameter below 20 μm and aluminum thickness of 35 nm electron trapping effects were observed down to UV power of approximately 500 μW.

6. Conclusions

Application of a laser allows local MOS structure properties to be measured by means of photoelectric techniques. The ϕ_{MS} distribution over the square gate of a MOS structure is such, that its values are highest far away from the gate-edge regions, lower in the vicinity of gate edges, and still lower in the vicinity of gate corners.

Laser beam can cause electron trapping and emission from the conduction band of the semiconductor. These phenomena may be investigated in photoelectric measurements with a laser as a UV-radiation source.

Comparison of the physical properties of differently shaped structures could be misleading due to edge effects. Measuring local parameter values one can avoid averaging values over central and edge regions of the gate and thus enhance measurement accuracy.

References

[1] C. H. Bjorkman, J. T. Fitch, and G. Lucovsky, "Correlation between midgap interface state density and thickness-averaged oxide stress and strain at SiO_2 interfaces formed by thermal oxidation of Si", *Appl. Phys. Lett.*, vol. 56, pp. 1983–1985, 1990.

[2] S. M. Hu, "Stress related problems in silicon technology", *J. Appl. Phys.*, vol. 70, pp. R53–R80, 1991.

[3] I. De Wolf, H. E. Maes, and S. K. Jones, "Stress measurements in silicon devices through Raman spectroscopy: bridging the gap between theory and experiment", *J. Appl. Phys.*, vol. 79, pp. 7148–7156, 1996.

[4] K. F. Dombrowski, I. De Wolf, and B. Dietrich, "Stress measurements using ultraviolet micro-Raman spectroscopy", *Appl. Phys. Lett.*, vol. 75, pp. 2450–2451, 1999.

[5] H. M. Przewłocki, "The importance, the nature and the measurements methods of the ϕ_{MS} factor in MOS structures", *Electron Technol.*, vol. 27, no. 1, pp. 27–42, 1994.

Lech Kazimierz Borowicz was born in Troki near Vilnus in 1934. He received the M.Sc. and Ph.D. degrees in electron technology in 1957 and 1967, respectively. He worked in five research institutes as Assistant Professor, as well as in industry, where he was involved in the design of equipment for spectral measurements. In 2001 he received a Silver Medal in the "Medicine and biotechnology" category at the International Exhibition of Inventions and Innovations for the retinometer – a laser device for estimation of potential visual acuity in the case of patients with cataract. He is the author and co-author of several tens of papers and other publications devoted to instrumental and physiological optics and optoelectronics, as well as organization and management of research.

Institute of Electron Technology
Lotników av. 32/46
02-668 Warsaw, Poland

Andrzej Kudła, Henryk P. Przewłocki, Danuta Brzezińska – for biography, see this issue, p. 39.