Paper

Comparison of the barrier height measurements by the Powell method with the ϕ_{MS} measurement results

Krzysztof Piskorski, Andrzej Kudła, Witold Rzodkiewicz, and Henryk M. Przewłocki

Abstract— In this work, we have compared the barrier height measurements carried out using the Powell method with the photoelectric effective contact potential difference (ϕ_{MS}) measurement results. The photoelectric measurements were performed on the samples that were previously applied in the investigation of the influence of stress on the duration of annealing in nitrogen. This paper shows that the results of barrier height measurement using the Powell method differ significantly from the ϕ_{MS} measurement results.

Keywords— barrier height, effective contact potential difference, MOS system.

1. Introduction

Significant differences between the values of barrier heights in the Al-SiO_2-Si structure found in the literature may be at least partly explained by the inaccuracies of the measurement methods and the lack of a sufficiently precise method of the verification of the obtained results.

The effective contact potential difference (ϕ_{MS}) is measured with the accuracy of ± 10 mV [4]. Having at our disposal such an extremely precise method of ϕ_{MS} measurement [4, 5] we have decided to use it to verify the results of the measurements of internal photoemission barrier heights in the MOS structure based on the Powell method [1, 2]. The accuracy of the barrier height (E_{BG} – metal-dielectric, E_{BS} – semiconductor-dielectric) measurements using the Powell method was estimated in [6] at ± 50 mV. Accordingly, we have compared the measurement results of E_{BG}, E_{BS} and ϕ_{MS}.

2. Theory

The internal photoemission phenomena may be observed in a MOS structure with a semitransparent gate, illuminated by UV radiation. The UV radiation absorbed in the electrodes (the gate or the substrate) causes the excitation of some electrons. If these electrons acquire sufficient energy to surmount the potential barrier at the electrode – insulator interface, they may pass into the insulator giving rise to a photocurrent in the external circuit. The measurement system for photoelectric measurements is shown in Fig. 1. The band diagram of the MOS system is shown in Fig. 2.

Balancing the potentials on both sides of the dielectric layer yields [6]:

$$\phi_M - U_G = \chi_{\mathrm{Si}} - \phi_I - \phi_S + \frac{E_{g,\mathrm{Si}}}{2q} + \phi_F \,, \qquad (1)$$

where: ϕ_M – the barrier height at the gate/dielectric interface, U_G – gate potential, χ_{Si} – the electron affinity of the silicon substrate at the interface, ϕ_I, ϕ_S – the potential drop in the dielectric and at the semiconductor surface, $E_{g,\mathrm{Si}}/2q$ – the voltage equivalent of half energy bandgap in the semiconductor, q – the electron charge, ϕ_F – the Fermi level.

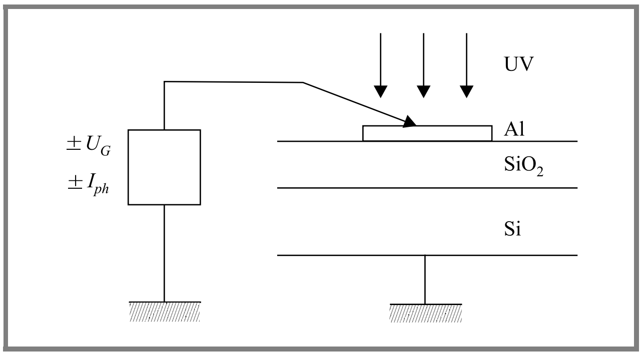

Fig. 1. The measurement system: a MOS structure with a semitransparent gate is illuminated by UV light. Photocurrent is measured in the external circuit.

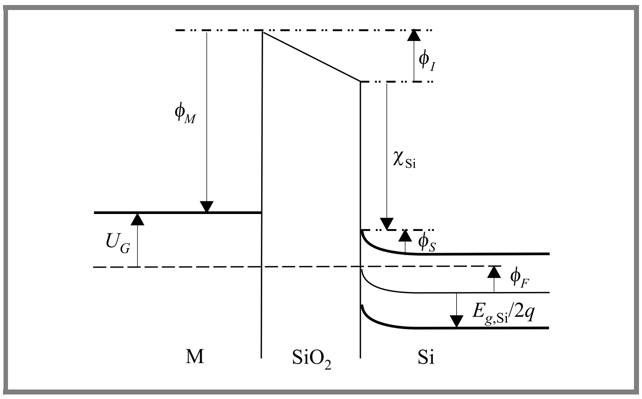

Fig. 2. Band diagram of a MOS system, at an arbitrary gate potential U_G.

The definition of the effective contact potential difference (ϕ_{MS}) offers the possibility of a comparison between the difference of internal photoemission barrier heights from both sides of the dielectric and the value of ϕ_{MS}.
The effective contact potential difference (ϕ_{MS}) is defined as:

$$\phi_{MS} = \phi_M - \left(\chi_{\mathrm{Si}} + \frac{E_{g,\mathrm{Si}}}{2q} + \phi_F\right). \quad (2)$$

The reduced effective contact potential difference (ϕ^*_{MS}) is defined as:

$$\phi^*_{MS} = \phi_M - \chi_{\mathrm{Si}} \quad (3)$$

or

$$\phi^*_{MS} = \phi_{MS} + \frac{E_{g,\mathrm{Si}}}{2q} + \phi_F\,. \quad (4)$$

The ϕ^*_{MS} value depends on the barrier height on both sides of the dielectric and does not depend on the doping concentration in the substrate.
To make our paper easier to read we propose the following symbols to denote the values of the reduced effective contact potential difference obtained using different methods:

- $\phi^*_{MS}(1)$ – the reduced effective contact potential difference determined on the basis of direct photoelectric measurements (4),
- $\phi^*_{MS}(2)$ – the reduced effective contact potential difference calculated (3) using the E_{BG} and E_{BS} values measured by the Powell method.

Subtracting (3) from (4) we have:

$$\phi^*_{MS}(1) - \phi^*_{MS}(2) = \phi_{MS} - \phi_M + \chi_{\mathrm{Si}} + \frac{E_{g,\mathrm{Si}}}{2q} + \phi_F = R\,. \quad (5)$$

The difference R is equal to 0 for an ideal measurement. Otherwise R stands for the error of the barrier-height measurement.
The value of R may be used to evaluate the accuracy of barrier height measurements. The ϕ_{MS} factor is determined from photocurrent measurement, while ϕ_F is determined from capacitance – voltage (*C–V*) measurements with the total accuracy better than 10 mV. In this case the value of R higher than 10 mV means that at least one of the considered barrier heights was measured inaccurately.

3. Experimental characterization

N-type (100) silicon wafers were used in this work. The wafers were doped with phosphorus to obtain the resistivity of 3–5 Ωcm. After the initial hydrogen-peroxide-based cleaning sequence, the wafers were thermally oxidized at 1000°C in oxygen to grow silicon-dioxide layers with the thickness of approximately 20, 60, and 160 nm. The wafers were subsequently annealed in nitrogen at 1050°C for periods of 0, 10, 120, and 1440 min. The gate metallization was carried out in a thermal evaporator so that the obtained Al thickness was 35 nm. Thin gate Al is necessary in MOS photoelectric measurements. The metallization was then patterned with optical lithography and the backside oxide was etched prior to the backside metalization. Postmetallization annealing was carried out in forming gas for 20 min at 450°C.

4. Experimental results and discussion

The wafers, used for the photoelectric measurements were previously applied in the investigation of the influence of stress on the time of annealing in nitrogen [3]. Accordingly, the photoelectric parameters (ϕ_{MS}, E_{BG}, E_{BS}) will be shown in this work as a function of the duration of annealing in nitrogen.

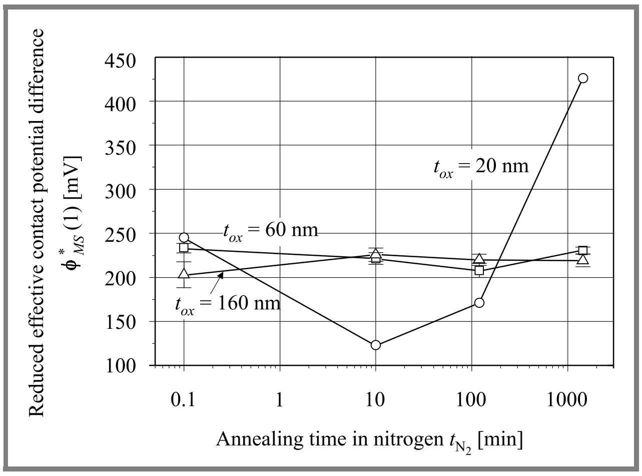

Fig. 3. The determined reduced effective contact potential difference $\phi^*_{MS}(1)$ versus the time t_{N_2} of annealing in nitrogen for oxide thickness of 20, 60, and 160 nm.

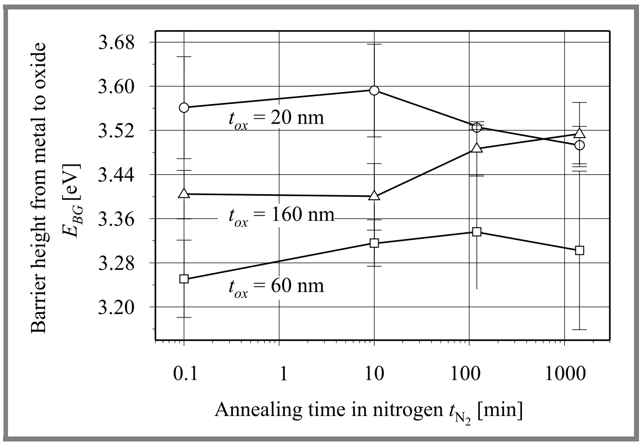

Fig. 4. Results of the E_{BG} measurements versus the time t_{N_2} of annealing in nitrogen for oxide thickness of 20, 60, and 160 nm.

The dependence of the determined reduced effective contact potential difference $\phi^*_{MS}(1)$ on the annealing time is shown in Fig. 3.

The dependence of the measured E_{BG} barrier on the annealing time for oxide thickness of 20, 60, and 160 nm is shown in Fig. 4.

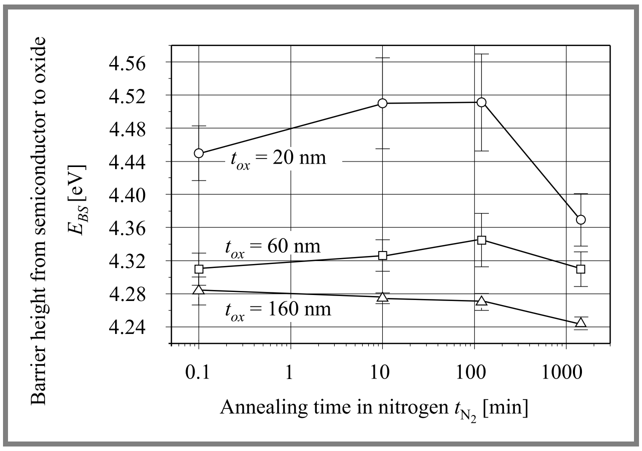

Fig. 5. Results of the measured barrier height between semiconductor and oxide E_{BS} versus the time t_{N_2} of annealing in nitrogen for oxide thickness of 20, 60, and 160 nm.

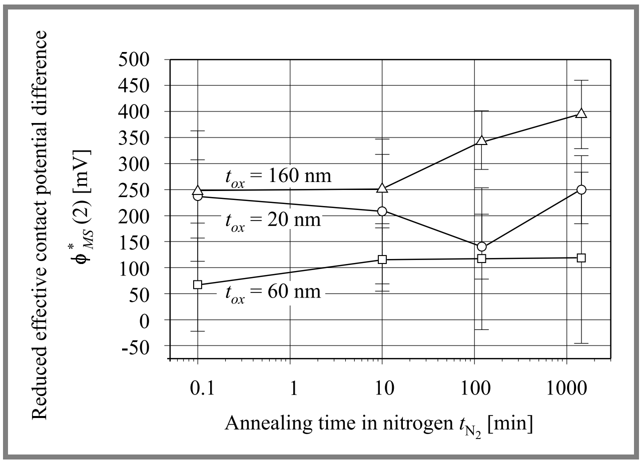

Fig. 6. The calculated effective contact potential difference $\phi^*_{MS}(2)$ versus the time t_{N_2} of annealing in nitrogen for oxide thickness of 20, 60, and 160 nm.

Table 1
Values of measurement error R

t_{N_2} [min]	R [mV]		
	t_{ox} [nm]		
	20	60	160
0	7.64	165.74	–43.26
10	–85.08	105.65	–25.3
120	30.78	90.33	–122.32
1440	176.08	111.84	–175.37

Figure 5 shows the dependence of the E_{BS} measurement results on the annealing time for oxide thickness of 20, 60, and 160 nm.

The dependence of the reduced effective contact potential difference $\phi^*_{MS}(2)$ (calculated on the basis of the measurements of the barrier heights E_{BG} and E_{BS}) on the annealing time is shown in Fig. 6.

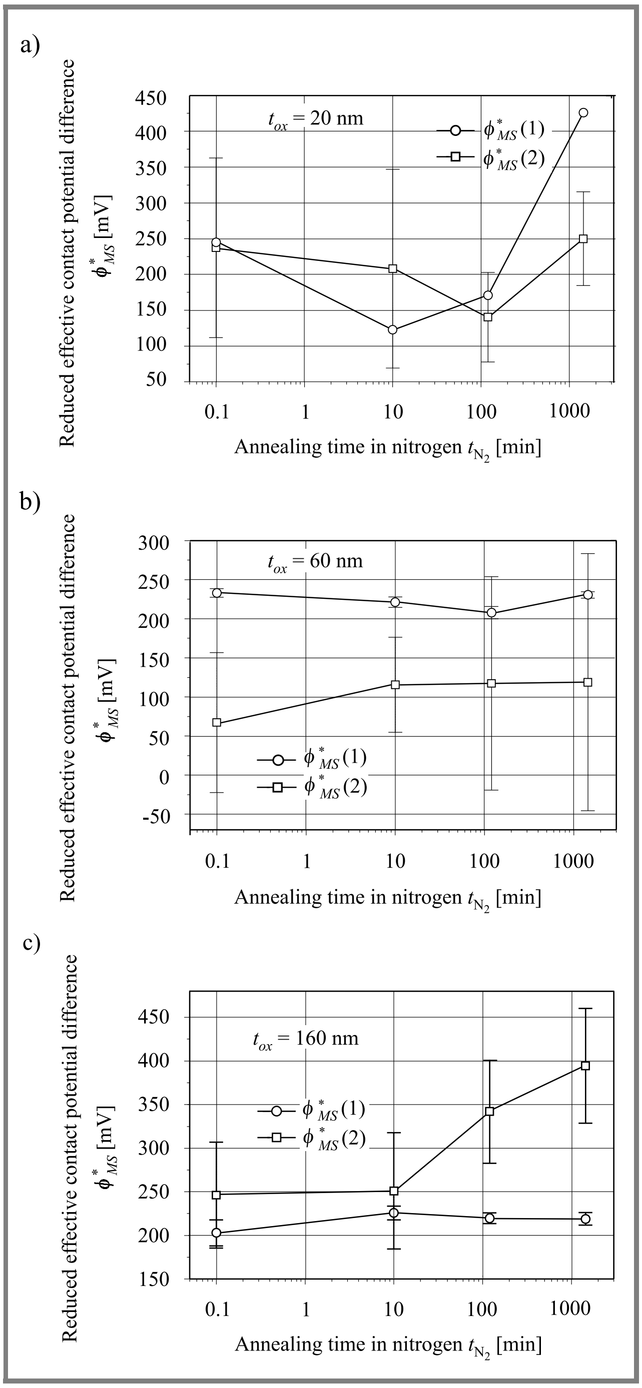

Fig. 7. Measured $\phi^*_{MS}(1)$ and $\phi^*_{MS}(2)$ calculated reduced effective contact potential difference versus the time t_{N_2} of annealing in nitrogen for oxide thickness of: 20 nm (a); 60 nm (b); 160 nm (c).

Subsequently, we have compared the values of $\phi^*_{MS}(1)$ and $\phi^*_{MS}(2)$ shown as a function of the annealing time in Fig. 7 for different oxide thicknesses.
The values of the R factor in [mV] determined from (5) are given in Table 1. The table indicates that the measurement error R can be both positive and negative.

5. Conclusions

In this work, we have compared the reduced effective contact potential difference $\phi^*_{MS}(1)$ (determined on the basis of the ϕ_{MS} measurement) with the reduced effective contact potential difference $\phi^*_{MS}(2)$ (calculated on the basis of the barrier height measurements using the Powell method).
This research shows (Fig. 7 and Table 1) that the barrier heights measured using the Powell method are significantly different from the results of ϕ_{MS} measurements. We attribute these differences to the poor accuracy of the Powell method.
It is believed that the main causes of this inaccuracy are:

– errors made in the extrapolation of *I–V* characteristics;

– improper values of the p-factor used for calculations of the barrier heights.

The positive value of the measurement error R may be explained by too low a value of the barrier height measured at the gate – SiO_2 interface or too high a value of the barrier height measured at the SiO_2 – semiconductor interface. The negative value of the error may be explained by too low a value of the barrier height measured at the SiO_2 – semiconductor interface or too high a value of the barrier height measured at the metal – SiO_2 interface. The non-zero value of R is in our view primarily caused by inappropriate values of the p-factor used in the barrier height determination.
In our further research we will focus on the main factors affecting the accuracy of the barrier height determination methods. In particular, the physical nature and the ways to choose the appropriate values of the p-factor will be studied.

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Andrzej Kudła, Henryk M. Przewłocki – for biography, see this issue, p. 39.

Witold Rzodkiewicz – for biography, see this issue, p. 119.