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Charge pumping characterization of MISFETs with $SiO_2/BaTiO_3$ as a gate stack

Abstract. *The results of charge pumping measurements of MISFETs with $SiO_2/BaTiO_3$ as a gate stack were presented and discussed. The characterization method was used for verification of thershold voltage and trap density values obtained by static current-voltage (I-V) measurements.*

Streszczenie. *W pracy zaprezentowano i przeanalizowano wyniki pomiarów tranzystorów MISFET wykorzystujących dwuwarstwowy dielektryk $SiO_2/BaTiO_3$. Pomiary wykonano przy użyciu metody pompowania ładunku. Stosowana metoda charakteryzacji posłużyła do weryfikacji wartości napięcia progowego tranzystora oraz gęstości pułapek powierzchniowych uzyskanych w oparciu o pomiar statycznych charakterystyk prądowo-napięciowych (I-V) tranzystora. (**Charakteryzacja tranzystorów MISFET z bramką $SiO_2/BaTiO_3$ metodą pompowania ładunku**).*

Keywords: charge pumping, high-k, MISFET, barium titanate, traps density.
Słowa kluczowe: metoda pompowania ładunku, wysoka przenikalność elektryczna, tranzystory MISFET, tytanian baru, gęstość pułapek.

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Introduction

Owing to advantageous electrophysical properties (in particular piezoelectricity, high dielectric constant and refractive index values), barium titanate $BaTiO_3$ (BT) ceramics have been one of the most extensively used dielectric materials in electronic applications, such as multilayer ceramic capacitors (MLCCs) [1], electro-optic modulators [2], microwave filters and resonators [3], optical waveguides [4], embedded capacitances in printed circuit boards [5], sensors and actuators [6]. In these areas of applications $BaTiO_3$ has been used in a bulk or a thick layer form. More recently, barium titanate has been also attracting attention as a potential high-k dielectric for applications in non-volatile memories (NVM) [7], dynamic random access memories (DRAM) [8] or ferroelectric random access memories (FRAM) [9], which however requires producing BT in the form of a thin film.

The fact that thin film BT also exhibits these properties makes it a potential candidate for use in numerous electronic and optoelectronic structures. These applications might be extended to the field of microelectronics, i.e. metal-insulator-semiconductor (MIS) structures [10].

This work presents the results of charge-pumping measurements of MISFETs with $SiO_2/BaTiO_3$ gate stack. The aim of these measurements is to provide information on the density of interface traps. Flat-band and threshold voltage, as well as the density of interface traps are determined.

Investigated structures

The first step of the fabrication process of MISFET with $SiO_2/BaTiO_3$ gate stack was thermal oxidation in order to obtain field oxide of about 440 nm. A p-type Si <100> oriented substrate with resistivity of 6-8 Ωcm was used. After first photolithography, drain and source areas were opened and doped with phosphorus. After cleaning processes 40nm thick SiO_2 film was produced by thermal oxidation and then approximately 80-nm thin barium titanite film was deposited by means of radio frequency plasma sputtering (RF PS) from a sintered $BaTiO_3 + La_2O_3$ (2 wt. %) target. Next photolithography allowed preparation of a photoresist mask for etching process. As a last step contacts for metallization were opened and aluminum was evaporated. A schematic cross-section of the final MISFET structure is presented in Fig. 1.

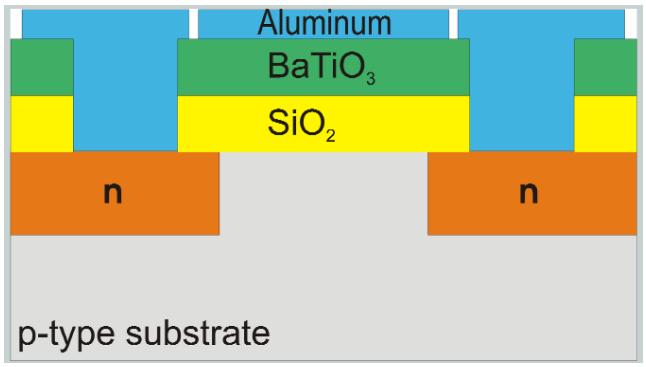

Fig.1. Schematic cross-section of the final MISFET structure

Gate length and width are 15 μm and 600 μm, respectively. The wafer with devices is shown in Fig. 2.

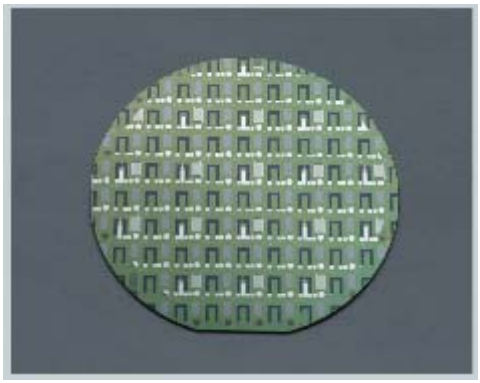

Fig.2. Si wafer with investigated devices

Measurements

Charge-pumping (CP), in its numerous forms, yields information on the density, energy levels and other properties of interface traps. Its main advantage is the fact that the device under test is a MOSFET, therefore no special test structures have to be fabricated. The method consists in switching the transistor between accumulation and strong inversion and measuring the DC substrate current that is caused by carrier recombination in interface traps. The maximum charge-pumping current I_{cpmax} is a measure of interface-trap density according to [11]:

(1) $$I_{cpmax} = q \cdot N_{it} \cdot A_g \cdot f$$

where: q - elementary charge, N_{it} - total density of interface traps per unit area, A_g - gate area, f - gate-signal frequency.

Equation (1) indicates that the maximum charge-pumping current is proportional to gate-signal frequency. Therefore the straight line obtained in Figure 3 indicates that the measured current is, indeed, related to charge-pumping.

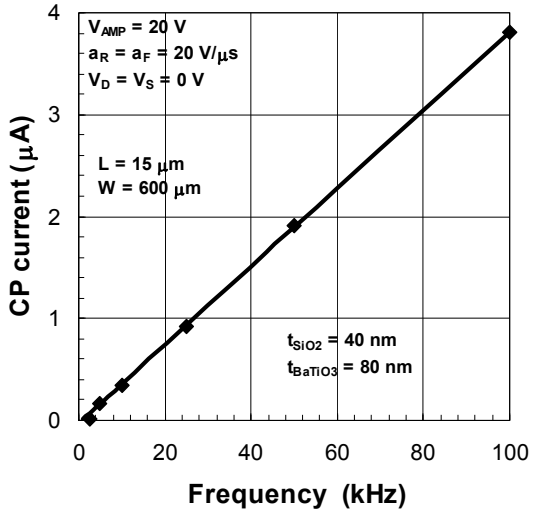

Fig.3. Maximum charge-pumping current as a function of frequency

The results of CP current measurements as a function of base voltage with gate-signal amplitude as a parameter are presented in Figure 4. The amplitude of the gate signal (parameter of the family of curves in the diagram) was changed from 10V to 20V (solid line) and then the whole measurement sequence was repeated (squares). The fact that the results of both experiments are very close indicates that no visible generation of interface traps was caused during measurements. Additionally, it may be seen that the CP current saturates if the signal amplitude is sufficiently high.

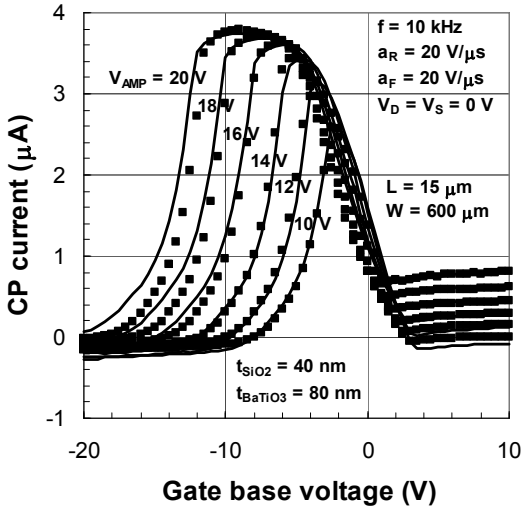

Fig.4. Charge-pumping current as a function of base voltage with gate-signal amplitude as a parameter

Analysis of the CP curves presented above yields the total density of interface traps N_{it}, as well as the threshold V_{th} and flat-band V_{FB} voltage (see Table 1) [12]. The obtained value of threshold voltage and density of interface traps were compared with those obtained from I-V characteristics. In case of I-V characteristics, the density of interface states was determined on the basis of subthreshold swing in weak inversion [13]. Examples of output and transfer I-V characteristics are presented in Figure 5a and 5b, respectively.

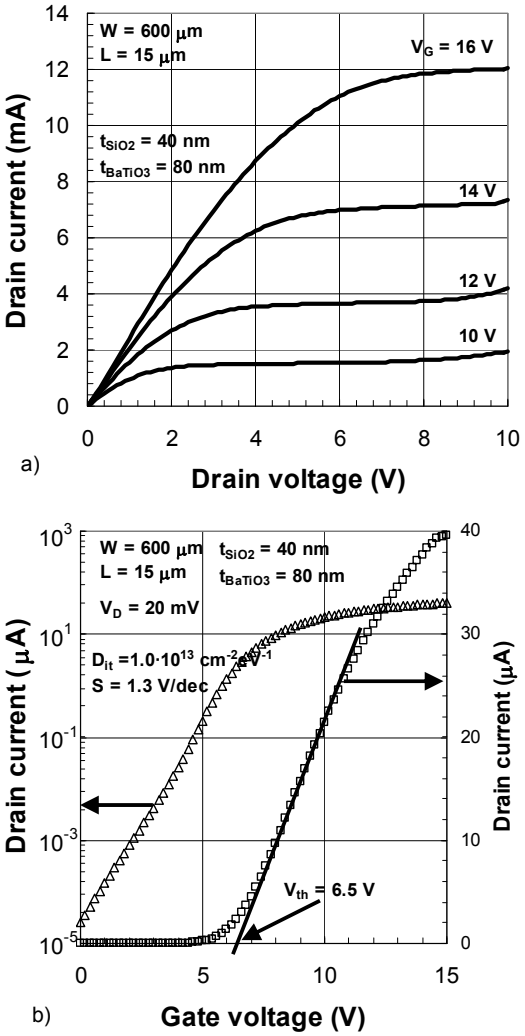

Fig.5. Output (a) and transfer (b) characteristics of transistor structures

Table 1. Parameters determined from C-P and I-V measurements

	N_{it} (cm^{-2})	V_{FB} (V)	V_{th} (V)
Charge pumping method	5.5·10^{13}	~-1.5	~7.0
Current-voltage method	1.0·10^{13}	-	6.5

The density of interface traps for different devices (with the same length and width) is presented in Figure 6. Huge difference in interface states density is observed, which could be due to non-uniform morphology of the insulating layer sputtered on the whole wafer.

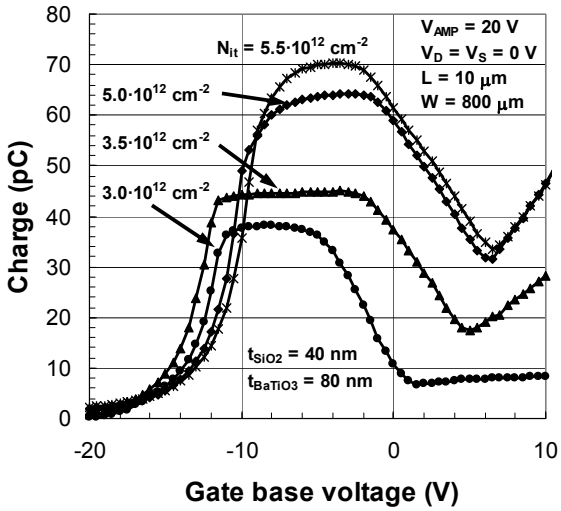

Fig.6. Comparison of charge pumped during one period of gate signal as a function of gate base voltage for different transistors

Conclusions

Charge-pumping measurements were performed for MISFETs with $SiO_2/BaTiO_3$ gate stack. Well-behaved CP curves were obtained. Flatband and threshold voltage, as well as total density of interface traps, were determined. Threshold-voltage values were in good agreement with those obtained from *I-V* curves.

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REFERENCES

[1] Wen H., Wang X., Gui Z., Li L., Modeling of the core-shell microstructure of temperature-stable $BaTiO_3$ based dielectrics for multilayer ceramic capacitors, *Journal of Electroceramics*, 21 (2008), 545-548

[2] De-Gui Sun at all, Performance simulation for ferroelectric thin-film based waveguide electro-optic modulators, *Optics Communications*, 255 (2005), 319-330

[3] Ioachim A. at all, Barium strontium titanate-based perovskite materials for microwave applications, *Progress in Solid State Chemistry*, 35 (2007), 513-520

[4] Chen F., Wang X. -L, Wang K. -M., Development of ion-implanted optical waveguides in optical materials: A review, *Optical Materials*, 29 (2007), 1523-1542

[5] Choa S. -D., Lee J. -Y., Hyuna J. -G., Paik K. -W., Study on epoxy/$BaTiO_3$ composite embedded capacitor films (ECFs) for organic substrate applications, *Materials Science and Engineering: B*, 110 (2004), 233-239

[6] Rattanachana S., Miyashitab Y., Mutoh Y., Fabrication of piezoelectric laminate for smart material and crack sensing capability, *Science and Technology of Advanced Materials*, 6 (2005), 704-711

[7] Ramesh R., Aggarwal S., Auciello O., Science and technology of ferroelectric films and heterostructures for non-volatile ferroelectric memories, *Materials Science and Engineering*, 32 (2001), 191-236

[8] Kuroiwa T. at all, Dielectric Properties of $(Ba_xSr_{1-x})TiO_3$ Thin Films Prepared by RF Sputtering for Dynamic Random Access Memory Application, *Japanese Journal of Applied Physics*, 33 (1994), 5187-5191

[9] Scott J. F., New developments on FRAMs: [3D] structures and all-perovskite FETs, *Materials Science and Engineering: B*, 120 (2005), 6-12

[10] Firek P., Werbowy A., Szmidt J., MIS field effect transistor with barium titanate thin film as a gate insulator, *Materials Science and Engineering: B*, 165 (2009), 126-128

[11] Brugler J. S., Jespers P. G. A., Charge pumping in MOS devices, *IEEE Transactions Electron De*vices, 16 (1969), 297-302

[12] Groeseneken G., Maes H.E., Beltran N., De Keersmaecker R. F., A reliable approach to charge-pumping measurements in MOS transistors, *IEEE Transactions Electron Devices*, 31 (1984), 42-53

[13] Van Overstraeten R. J., Decklerck G. J., Muls P. A., Theory of the MOS transistor in weak inversion-new method to determine the number of surface states, *IEEE Transactions Electron Devices*, ED-22 (1975), 282-288

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