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A Holographic View Inside a MOS Capacitor

Extended Charge Layers in Metal-Oxide-Semiconductor Nanocapacitors Revealed by *Operando* Electron Holography
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Recommended with a Commentary by Joe Checkelsky, Massachusetts Institute of Technology

The metal-oxide-semiconductor (MOS) structure plays a central role in integrated circuits including as the active channel in field effect transistors. Intense research in the 1960s demonstrated that oxidizing Si into SiO_2 creates a high-quality oxide-semiconductor interface; despite interest in novel materials to replace it, SiO_2 remains ubiquitous as a dielectric oxide, with popular estimates suggesting that more than 10^{22} SiO_2-based transistors have been manufactured to date. An important parameter for the performance of these capacitors is the threshold voltage V_{th} (the voltage at which the device changes from depletion to inversion). Imperfections such as charge traps in the bulk of the insulator or at the interfaces can create unwanted modifications to V_{th} and other critical device parameters. A textbook example of such a trap is that naturally occurring at the interface between the crystalline Si and amorphous SiO_2, where the misfit nature of the interface gives rise to unpassivated bonds [1]. From Poisson's equation, the presence of such charge traps directly modifies the electric potential of the MOS capacitor, modifying its switching characteristics including V_{th}. If, further, such charges are mobile (*e.g.* Na contaminants), long term stability issues arise.

Given the importance of understanding MOS performance, a wide array of characterization techniques has been used to probe charge in these structures since their initial development [2]. The majority of these are "global" probes such as internal photoemission [3] which, while quantitative, are unable to address the location of charges within the MOS structure. Such information is crucial in enabling the microscopic understanding of impediments to device operation. Real-space techniques such as scanning capacitance microscopy have been applied [4], but are often obfuscated by the role of the scanning tip itself in the characterization. Ideally, one would image directly the electric potential in a non-invasive manner. Further, this would most informatively be done in a structure that is a close facsimile of a device configuration to examine technologically relevant conditions.

Electron holography – the use of interference of coherent electron waves for imaging - is a well-suited probe for such studies [5]. The concept of electron holography was first put forward by Gabor in 1949 as a method to improve the resolution of electron microscopy [6];

while originally implemented in optics, with the development of the stable coherent electron gun the technique has become a widely used tool in electron microscopy. Electron holography can be used to probe the phase of the electron and is thus sensitive to the geometric path length, the electrostatic potential, and the magnetic vector potential in an observed specimen. The last has been key to recent advances in condensed matter physics in *e.g.* the quantitative study of Skyrmions [7] while the imaging of the electric potential has been explored in the naturally occurring electric field of *p-n* junctions [8]. Extending the latter to imaging of devices in the mode of operation has been of significant interest.

In the highlighted work, Gatel *et al.* have applied electron holography to a Ti-SiO_2-Si MOS capacitor to which they can further apply voltages during imaging. Extending previous transmission electron microscopy studies which applied *in-situ* voltages to structures using a nanoprobe (as in *e.g.* [9]), they employ a focused ion beam (FIB) preparation technique to prepare a “specimen device” with electrical connections relatively free of unwanted stray electric fields. This enables holographic imaging of a nanocapacitor geometry with and without a bias applied; the latter is then used as a reference for the former to remove artifacts and isolate the role of charging the capacitor. The capacitor itself has an approximately 100 nm thick dielectric to which a voltage up to 5 V is applied- the phase sensitivity of 10 mrad (corresponding to approximately 10 mV in the analysis of the holographic image) and sub-nanometer real space resolution offer a clear view inside of the biased MOS system.

After verifying the generally expected systematics- in particular that the electronic phase winding increases linearly with applied voltage in a manner quantitatively consistent with expectations – the authors report an unexpected discovery: with applied voltage, there is an enhanced winding of phase shift extending approximately 5 nm into the dielectric at both interfaces of the MOS capacitor. Modeling of this winding is consistent with the presence of charge layers similar to which those formed as electric double layers in electrochemical charging [10], but here in the form of hundreds of elementary charges (of sign opposite to the nearby electrode) gathering at the solid-state Si-SiO_2 and Ti-SiO_2 interfaces. This spatially extended and evidently equilibrium charge distribution is surprising and suggests there are an order of magnitude more active charges in the electrode and charge layer than expected for an ideal capacitor. This has myriad implications for device performance including for V_{th} and stability with the enhanced electric field and calls for a potential reexamination of the role of non-ideal charges at the MOS interface.

While the holographic images taken here are of a device which has important differences from those used in modern transistors (including that it is studied in a DC bias operation only), they are striking in that they immediately challenge the conventional view of how a ubiquitous microelectronic component operates at the nanoscale. This behavior would have been invisible to conventional global measurement methods and was observed here leveraging the capabilities of electron holography to probe both the location and quantitative nature of potentials in a nanostructure. With increasingly advanced methods of FIB structuring [11] and holographic and advanced scanning probe imaging [12] being applied to quantum materials, it is interesting to consider what other surprises might await observation by these advanced methods applied to conventional technological structures. Combining such methods with quantum metrology [13] might not only open new vistas for future quantum technologies, but also break ground in the understanding of those devices already deployed in the technology around us.

References

[1] S.M. Sze and K. K. Ng, in *Phys. Semicond. Devices* (John Wiley & Sons, Ltd, 2006), pp. 197–240.

[2] O. Engström, in *The MOS System* (Cambridge University Press, Cambridge, 2014), pp. 131-220.

[3] V. K. Adamchuk and V. V. Afanas'ev, Prog. Surf. Sci. **41**, 111 (1992).

[4] R. N. Kleiman *et al.*, in *Int. Electron Devices Meet. IEDM Tech. Dig.* (1997), pp. 691–694.

[5] A. Tonomura, Rev. Mod. Phys. **59**, 639 (1987).

[6] D. Gabor and W. L. Bragg, Proc. R. Soc. Lond. Ser. Math. Phys. Sci. **197**, 454 (1949).

[7] H. S. Park *et al.*, Nat. Nanotechnol. **9**, 337 (2014).

[8] A. C. Twitchett *et al.*, Microsc. Microanal. **11**, 66 (2005).

[9] L. de Knoop *et al.*, Micron **63**, 2 (2014).

[10] J. O. Bockris and A. K. N. Reddy, in *Vol. 2 Mod. Electrochem. Introd. Interdiscip. Area*, (Springer US, Boston, MA, 1970), pp. 845–990.

[11] P. J. W. Moll, Annu. Rev. Condens. Matter Phys. **9**, 147 (2018).

[12] K. A. Moler, Nat. Mater. **16**, 1049 (2017).

[13] C. J. Williams, Proc. Int. School of Phys. Enrico Fermi **196**, 309 (2017).