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Application Note

Keywords: MOSFET gate stacks, Band bending, Doping effects, Interface electronic states

Bias Dependent Band Structure Analysis in MOS Devices via Ga-Kα Laboratory HAXPES

Introduction

Understanding the band structure of a semiconductor is essential, as it defines the intrinsic energy landscape that governs carrier dynamics. When subjected to external electric fields, doping, or interface effects, this band structure undergoes local shifts—known as band bending. These shifts reflect the redistribution of charge within the material and play a pivotal role in device operation.

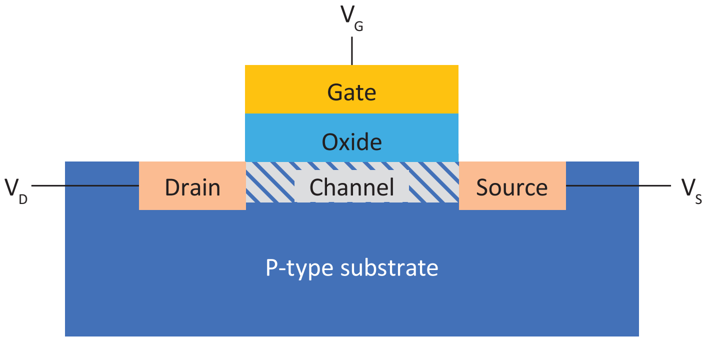


Figure 1: MOSFET illustration.

In metal–oxide–semiconductor field-effect transistors (MOSFETs), band bending beneath the gate electrode dictates whether the semiconductor enters accumulation, depletion, or inversion regimes. For example, in p-type silicon:

- Upward band bending leads to depletion or inversion, enabling the formation of a conductive channel (MOSFET "on" state).
- Downward band bending causes accumulation, keeping the device in its "off" state.

Accurately measuring band bending under operational conditions provides critical insight into electrical behavior, interface quality, and doping effects, which are all central to the performance and reliability of modern semiconductor devices. Traditional techniques however struggle to probe the necessary buried interfaces nondestructively. This paper presents a laboratory-based Ga-Kα HAXPES method for in situ investigation of band structure and potential shifts non-destructively, within working MOS structures.

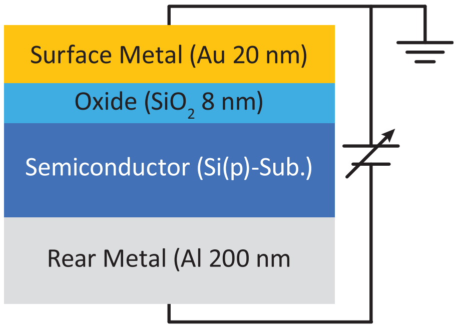


Figure 2: Schematic of the MOS stack in the paper of Minowa et al.

Objective

Demonstrate how HAXPES, and in particular Ga-Kα Laboratory HAXPES, can non-invasively monitor bias-induced band bending and interface electronic states in MOS devices with varying silicon substrate doping.

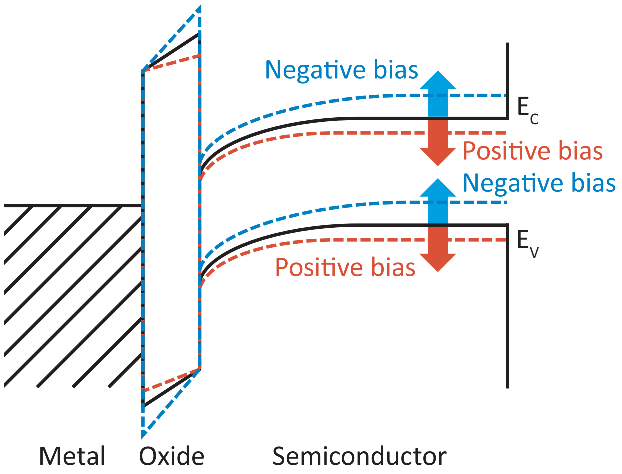


Figure 3: Illustration of how the energy bands within the MOS structure respond to applied bias relative to the unbiased condition (0 V), in the case where the metal gate is on ground as shown in Figure 2.

Methods and Results

- Utilized a Scienta Omicron laboratory HAXPES instrument with LiquidJet X-ray source (Ga-Kα) for high-energy photons ensuring deeper probing depth.
- Studied Au/SiO_2/Si MOS samples with different Si doping levels.
- Applied variable external bias to investigate peak shifts in core-level spectra (e.g. Si 2p, O 1s).

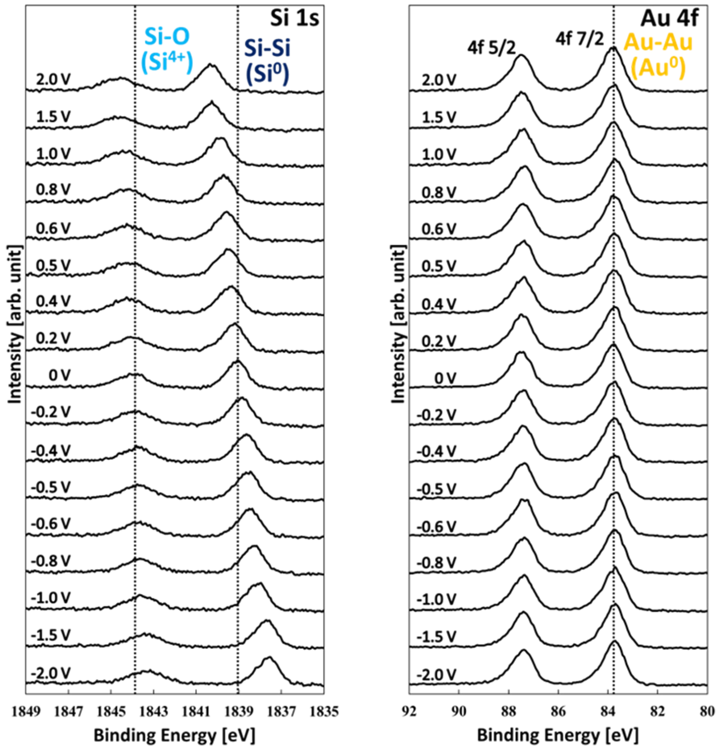


Figure 4: Bias Applied (BA-)HAXPES spectra for the 5.70-Ω·cm) sample: The Si 1s spectra shift with applied bias whereas the Au 4f is grounded and constant in binding energy.

The change in BE shift — from linear to nonlinear — marks the transition from depletion to accumulation or inversion.

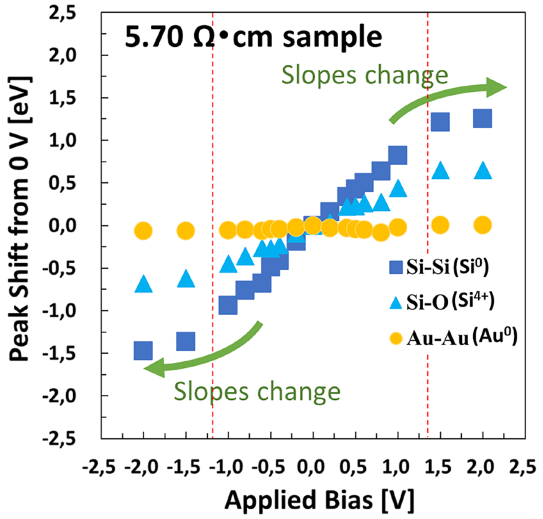
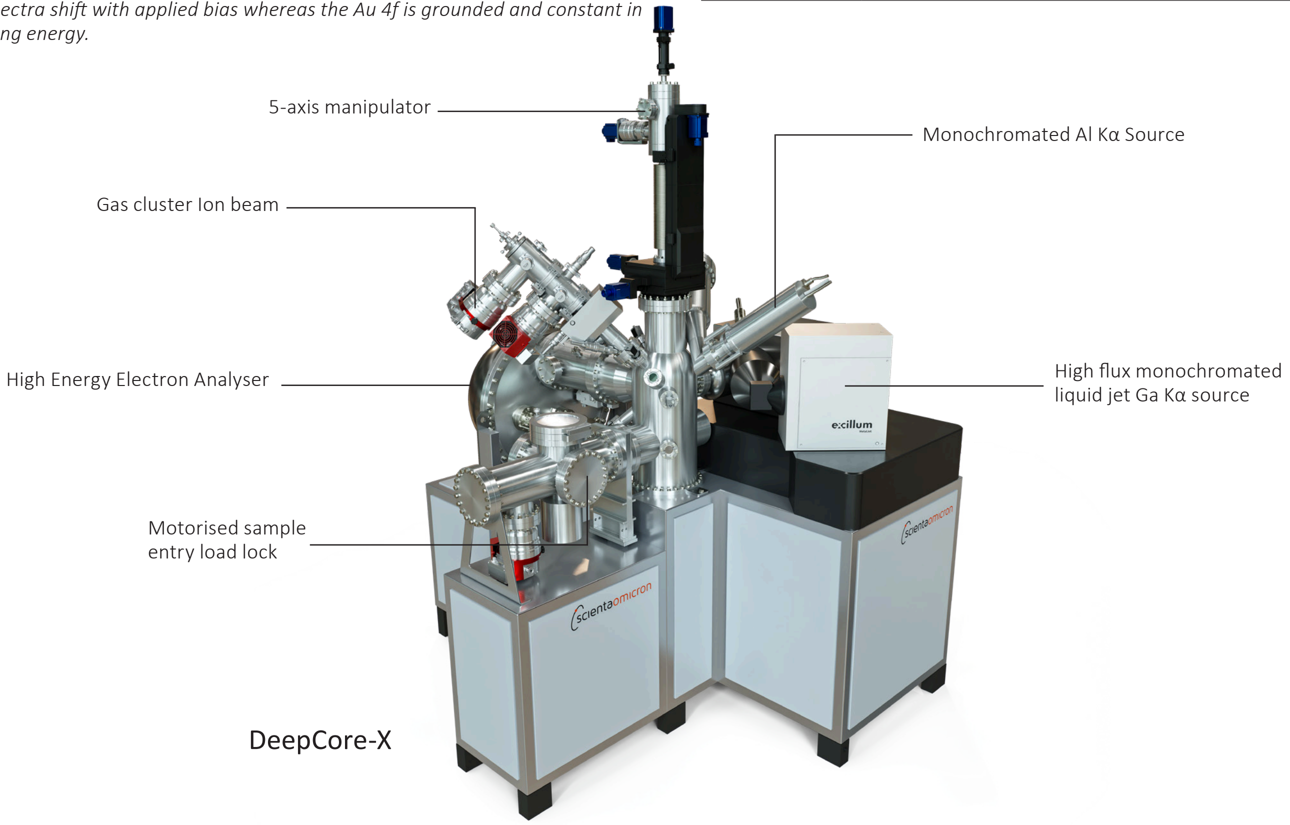


Figure 5: Plot of applied bias vs measured peak shifts from Figure 4 along with analysis.

Applied Bias	
-1.5 to -2 V	Change from linear is decreased. Strong inversion state in the Si layer.
-0.5 to -1.5 V	Deviation from linear. Transition into inversion state.
+/-0.5 V	Linear peak shift with applied bias (depletion).
0.5 to 1.5 V	Start of deviation from linear. Transition into accumulation state.
1.5 to 2 V	Distinct change, likely due to the metallic behavior of the accumulation layer



Scienta Omicron laboratory HAXPES instrument measurements directly confirm how different doping concentrations (e.g., 5.70 vs. 0.49 Ω·cm) affect when and how accumulation-depletion-inversion transitions occur.

Controlling the inversion onset and threshold voltages allow customizing device behavior trading off e.g. speed, power consumption, and stability.

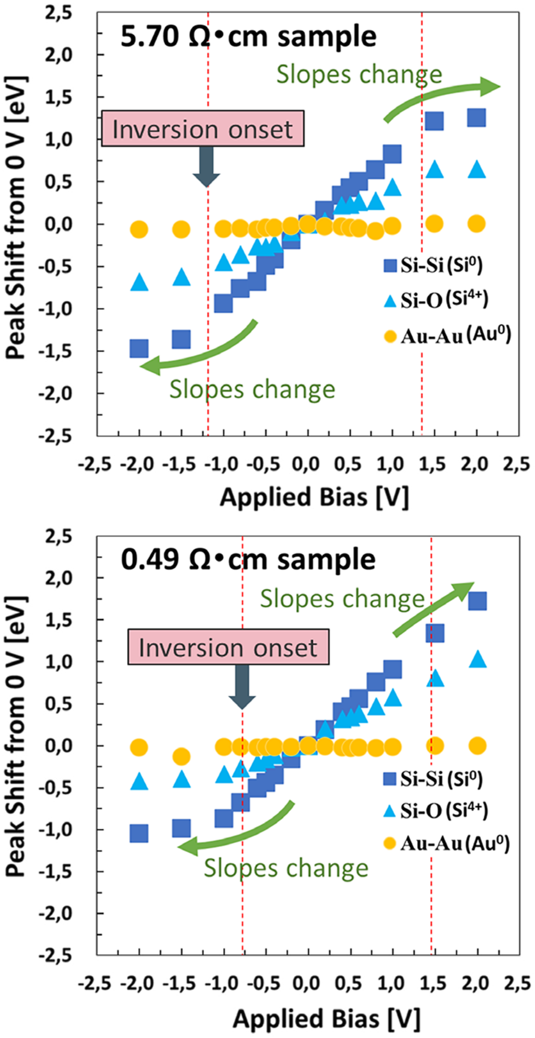


Figure 6: Comparison of different substrate doping concentrations revealing e.g. earlier inversion onset in the higher doping case.

Results and Insights

- Revealed clear quantitative shifts in Si 1s applied bias, enabling precise band bending calculations.
- Observed a strong doping-dependence:

  0.49 Ω·cm (higher doping):

    Earlier onset of inversion

    Narrower depletion width (linear region)
- Confirmed feasibility of using laboratory Ga source HAXPES for detailed, real-time electronic investigation of functional devices.

Conclusion

Ga-Kα laboratory HAXPES offers a robust platform for in situ, nondestructive characterization of MOS interfaces under bias. Its ability to directly track band bending at buried interfaces across doping variations makes it invaluable for semiconductor device research and quality assurance.

Key Benefits of Ga-Kα HAXPES

1. Nondestructive Probing of Buried Interfaces

   Ga-Kα photons (9.25 keV) penetrate through gate metal and oxide layers, enabling direct observation of electronic structure changes at the SiO_2/Si interface without removing layers.

2. Direct Monitoring of Bias-Dependent Band Bending

   Under varying bias, measured core-level shifts correspond directly to band bending in the silicon substrate.

Recommended for

- Device engineers evaluating MOSFET and gate-stack performance under bias
- Researchers analyzing interface defects, band alignment, and doping effects
- Labs seeking access to hard X ray insights without relying on synchrotron facilities

Reference:

Minowa, T., Usuda, K., Yokogawa, R., Ogura, A., 2025. Applied Physics Letters 126, 072103.