Student Paper

A III-V Field Effect Transistor (FET) with Hafnium Oxide Gate Dielectric for the Detection of Deoxyribonucleic Acid (DNA) Hybridization

Nicholas M Fahrenkopf, Padmaja Nagaiah, Natalya Tokranova, Serge Oktyabrsky, Vadim Tokranov, Magnus Bergkvist, Nathaniel C Cady

College of Nanoscale Science and Engineering, University at Albany, USA, ncady@albany.edu

Field-portable DNA biosensors have the potential to greatly improve diagnosis of disease, forensic DNA analysis, food safety monitoring, and biowarfare detection. These sensors detect hybridization of complementary strands of DNA, one immobilized onto the sensor substrate and the other free in solution. Most DNA sensors suffer from lack of portability or the inability to process large numbers of samples in parallel. Field effect transistor (FET) based DNA sensors, which detect hybridization by sensing negative charges on target DNA through the field effect, have the potential for both high throughput and portable detection [1].

In this work we present a novel depletion mode FET sensor that incorporates: 1) III-V semiconducting materials, 2) a hafnium oxide gate dielectric, and 3) direct immobilization of DNA to the surface. Our work differs from previously demonstrated FET biosensors that use doped silicon semiconductors with a silicon dioxide gate dielectric and complex crosslinking chemistry between the surface and the DNA [1]. We hypothesize that depletion mode FETs are more sensitive, due to the lower density of states in the III-V materials (AlGaAs/InAlAs) [2]. Further, our novel method of directly immobilizing DNA onto the gate significantly simplifies sensor fabrication and brings DNA closer to the sensor surface. This places the majority of the DNA within one Debye length from the gate oxide surface, which potentially increases device sensitivity [3].

Figure 1, bottom left, shows a schematic cross section of the FET that was designed and fabricated. Semi-insulating (SI) InP was used as a substrate and molecular beam epitaxy (MBE) was used to lattice matched grow the III-V layers followed by in-situ growth of hafnium oxide by reactive electron beam evaporation of metallic hafnium in oxygen. Standard photolithography, reactive ion etching, metal evaporation, and rapid thermal annealing was used to fabricate contacts, and isolate individual devices. Finally, photoresist was used to insulate the contact leads, leaving only the HfO_2 gate region and contact pads exposed. Polydimethylsiloxane (PDMS) was used to create a reservoir to allow placement of liquids on the gate area without shorting the source to drain. Figure 2, top, shows the ability of the FETs to detect increasing concentrations of double-stranded lambda DNA (48 kbp long). Single strand phosphorylated DNA (29 bp long) was patterned onto the exposed gate dielectric using a BioForce Nano-enabler quill pen printing tool. Figure 2, bottom left, shows the ability of the FET to detect the immobilization of the DNA even after rinsing. In comparison, Figure 2, bottom right, shows the FET does not respond to the biological buffer (Tris-EDTA) that the DNA is suspended in. To our knowledge, this is the first demonstration of FET-based sensing of DNA using probes directly linked to the gate surface via phosphate-dependent immobilization.

References

[1] F. Teles and L. Fonseca, “Trends in DNA biosensors,” Talanta, vol. 77, no. 2, pp. 606-623, Dec. 2008.
[2] S. Oktyabrsky, et al., “Challenges and progress in III-V MOSFETs for CMOS circuits,” International Journal of High Speed Electronics and Systems, vol. 18, no. 4, p. 761, 2008.
[3] E. Stern, et al., “Importance of the Debye screening length on nanowire field effect transistor sensors,” Nano Letters, vol. 7, no. 11, pp. 3405-9, Nov. 2007.

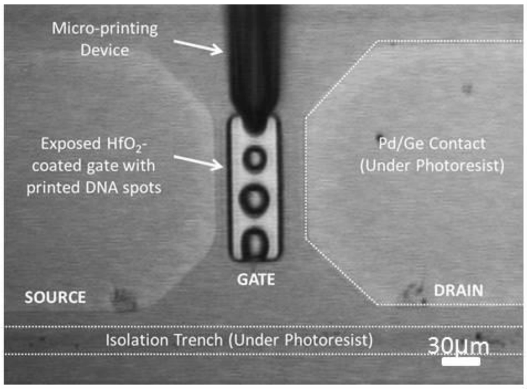
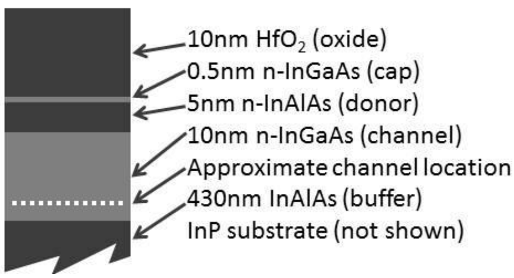
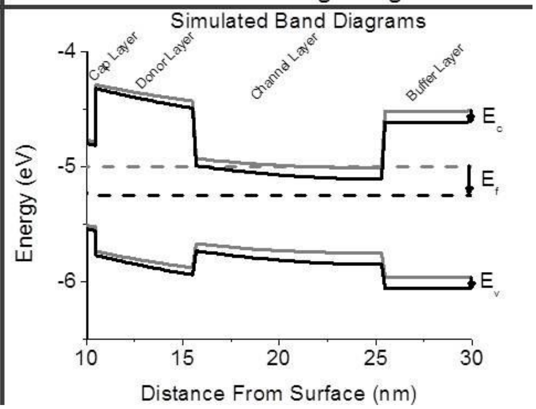


Figure 1. Top: Optical micrograph showing the source/drain contacts protected from liquid under a photoresist layer, while the gate region is exposed for printing of DNA. **Bottom:** Schematic cross section of device and simulated band diagrams for device at rest (**gray lines**) and with -250mV on the gate (**black lines**) (right). With a negative V_g, the conductive channel located approximately 23nm into the device is significantly reduced. Negative charges from DNA over the gate dielectric would mimic a negative gate bias.

Schematic cross section of device structure reflected in band diagrams (right). Note: HfO_2 layer not shown in band diagrams.





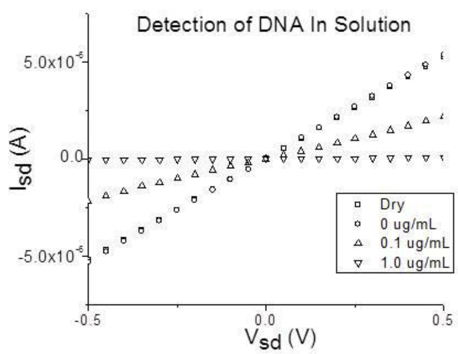


Figure 2. Top: Current-voltage (IV) curves showing an increase in source-drain resistance (R_{sd}) as increasing concentrations of DNA cover the exposed gate dielectric. **Bottom:** IV curves of devices before and after printing with DNA in a biological buffer (**left**) and printing with buffer alone (**right**). Both were then rinsed with buffer and measured again. R_{sd} remains decreased on the DNA printed device, whereas the buffer control device does not show a significant response.