Fabrication and Characterization of Diamond FETs with 2D Conducting Channels

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Keywords: Diamond, Field Effect Transistor, Hydrogen-Terminated, 2D, Al_2O_3

ABSTRACT

Field effect transistors (FETs) have been fabricated on smooth (< 3 Å RMS roughness) hydrogen-terminated diamond substrates. FETs with a 25 nm thick Al_2O_3 dielectric exhibited slightly normally-off behavior with threshold voltage of -0.8 V and maximum output current of 36.8 mA/mm at -10V drain bias. Open air storage and testing of the devices resulted in no shifts in the transfer characteristics, although a slight degradation in output current was observed. The degradation in drain current is believed to be due to passivation of the hydrogen termination by atmospheric contaminants penetrating the Al_2O_3 dielectric layer.

INTRODUCTION

The performance projections for diamond-based electronics for high power, high frequency applications are well documented [1]. Diamond exhibits ideal properties for such applications, including 5.5 eV bandgap, >10 MV/cm breakdown strength, theoretical electron and hole mobilities exceeding 3800 $cm^2/V*sec$, and outstanding 22 W/cm·K thermal conductivity. However, achieving useful carrier densities in diamond is challenging, as typical dopants have activation energies greater than 0.37 eV [2]. This limitation can be overcome by exploiting hole conductivity along 2D conducting channels to fabricate operational field-effect transistors (FETs). Such channels can be created through hydrogen termination of diamond surfaces. Exposing diamond to a hydrogen plasma produces a surface C-H dipole layer that significantly reduces the carrier ionization energy. Adsorbed gaseous species, such as H_2O or NO_2, or high electron affinity oxides contact this dipole layer and generate a near-surface two-dimensional hole gas (2DHG) with carrier densities of 10^{12}-10^{14} holes/cm^2 [3-4]. While devices based on hydrogen-terminated diamond have shown great promise, their long-term stability and reliability requires further assessment. In this work, we will discuss the fabrication, characterization, and stability of diamond FETs with Al_2O_3 dielectrics on ultra-smooth hydrogen-terminated diamond substrates.

SUBSTRATE PROCESSING AND CONDUCTIVITY GENERATION

Undoped (100) type IIa single crystal high pressure high temperature (HPHT) substrates (New Diamond Technology) were selected for use due to their very low dislocation density. In order to minimize carrier scattering within the 2DHG, substrates were polished and etched with a low power plasma [5] to less than 3 Å roughness, as indicated by atomic force microscopy (AFM) shown in Fig. 1.

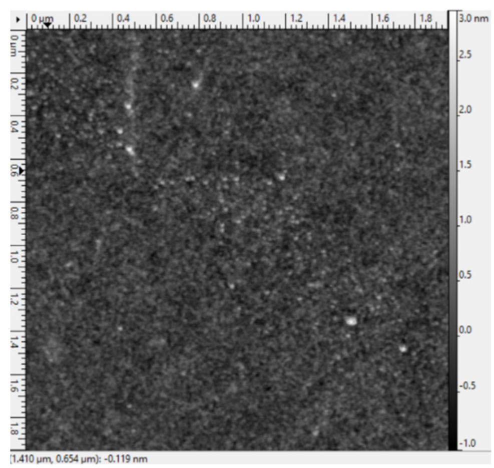

Fig. 1. AFM image of a typical diamond surface polished and etched to a <3 Å RMS surface roughness.

Hydrogen termination of the surface was achieved by exposing the polished surface to a hydrogen plasma at temperatures above 700 °C. The resulting C-H bonds create a negative electron affinity surface which, in the presence of so-called "surface transfer dopants", including atmospheric moisture and contaminants, easily surrenders electrons from the valence band and leaves behind a conductive 2DHG near the surface [6]. This can be observed with current-voltage (I-V) measurements between two Au contact pads on the hydrogenated sample surface exposed to air, as shown in Fig. 2. However, atmospheric H_2O and gaseous adsorbates such as NO_2 are inherently unstable transfer dopants; therefore, high electron affinity dielectrics, such as Al_2O_3, V_2O_5, and MoO_3 are of tremendous interest for stable and reliable hydrogen-terminated FETs [7-10]. Al_2O_3 was employed in this work due to its wide availability and ease of processing.

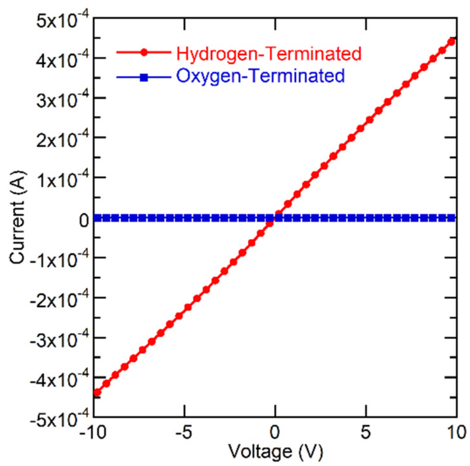

Fig. 2. Two-point I-V measurements between Au contacts ~ 25 µm apart, showing conduction along the H-terminated surface with unintentional atmospheric adsorbates. Oxygen plasma exposure destroys the hydrogen termination and thus the surface conductivity.

DEVICE FABRICATION

FETs, shown schematically in Fig. 3, were fabricated on these ultra-smooth hydrogen-terminated HPHT substrates. First, a 100-150 nm layer of Au was deposited by e-beam evaporation on the entire sample to protect the surface termination during subsequent processing steps. Photoresist mesas were patterned on the blanket Au layer, followed by wet etching in KI/I_2 (Au Etchant TFA, Transene Co.) to form discreet Au device mesas. A brief O_2 plasma etch was used to destroy the hydrogen termination and achieve device isolation. Discrete Ohmic contacts were then formed from the Au mesas by photolithography and KI/I_2 wet etchback. A blanket 25 nm Al_2O_3 film was used as the surface transfer dopant and gate dielectric, deposited by atomic layer deposition (ALD) at 175 °C with trimethylaluminum and water precursors. Windows were etched through the Al_2O_3 over the Ohmic contacts. Finally, 100 nm Al was deposited by e-beam evaporation and liftoff to form the gates.

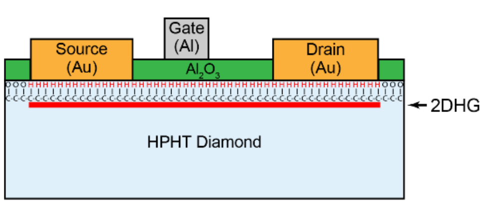

Fig. 3. Hydrogen-terminated diamond FET schematic with Al_2O_3 gate dielectric and surface transfer dopant.

FET PERFORMANCE AND STABILITY

Transfer and output characteristics for an Al_2O_3/diamond MOSFET with a 4 µm gate-to-drain spacing are shown in Fig. 4 below, with useful extracted device parameters in Table I. The device output current was comparable to other Al_2O_3/diamond FETs without NO_2 passivation [11]. The devices were slightly normally-off, with a threshold voltage (V_t) of -0.8 V, and exhibit an on/off current ratio of 10^4 mA/mm at a drain-source bias of -5 V.

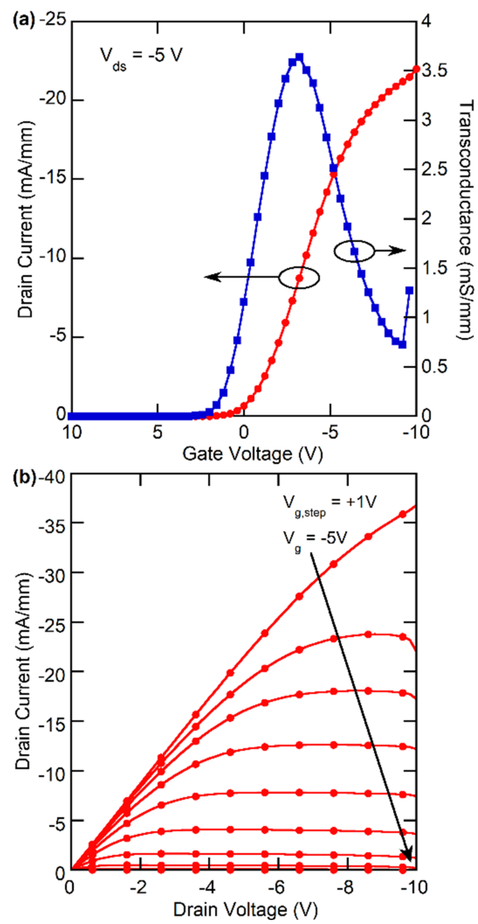

Fig. 4. (a) Turn-on and (b) output characteristics of an Al_2O_3/hydrogen-terminated diamond FET with gate length of 3 µm and gate-drain spacing of 4 µm.

TABLE I
Al_2O_3/H-TERMINATED DIAMOND MOSFET PARAMETERS

Parameter	Value
V_t	-0.80 V
$g_{m,max}$	3.64 mS/mm
I_{off} (V_{ds} = +10 V)	8.23×10^{-4} mA/mm
$I_{ds,max}$	36.8 mA/mm
R_{on}	230 Ω·mm

Operational stability is a concern for hydrogen-terminated diamond devices. While the use of dielectrics as surface transfer dopants should stabilize the 2DHG and the resulting device performance, thin or low-quality dielectrics may be insufficient to shield the hydrogenated surface from atmospheric contaminants. In order to assess the stability of the Al_2O_3/diamond MOSFETs produced in this work, multiple device measurements were taken over the course of one week. These measurements are shown in Fig. 5. Slight degradation in output characteristics were observed; on-resistance increased by 54 Ω·mm (27%) between the initial and final measurements, while output current decreased by 4 mA/mm (11%). Changes in V_t and $g_{m,max}$ were negligible over the same measurement period. This indicates that there is minimal gate charge trapping at the Al_2O_3/H-diamond interface, such that trapping is not responsible for the reduction in output. Instead, the Al_2O_3 may not provide complete protection of the hydrogen-terminated surface from atmospheric contamination. Such contaminants could penetrate the Al_2O_3 layer through pinholes or other small defects and passivate the hydrogen on the diamond surface, thereby causing the output degradation by reducing the 2DHG carrier density. This can be confirmed by future testing of the devices and additional Hall effect measurements in vacuum or in a dry N_2 atmosphere.

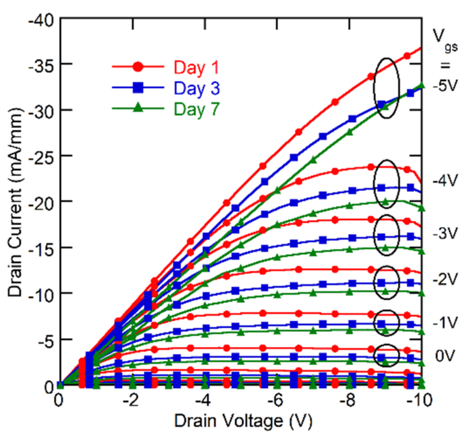

Fig. 5. Output characteristics showing a minor decrease in output current for the same device used in Fig. 4 over repeated measurements up to a week apart.

Conclusions

FETs have been fabricated on hydrogen-terminated diamond substrates. Surfaces with less than 3 Å roughness were obtained prior to hydrogen termination. Hydrogen termination was achieved by exposing the substrates to a pure hydrogen plasma at 700 °C. FETs fabricated on the hydrogen-terminated surface utilized a blanket Al_2O_3 dielectric as the surface transfer dopant and exhibited slightly normally-off behavior and well-behaved transistor characteristics, with V_t of -0.8 V and $I_{ds,max}$ of 36.8 mA/mm. Device stability was assessed through repeated measurements in laboratory air over the course of one week. Negligible changes in V_t or $g_{m,max}$ were observed, but a slight degradation in output current was observed. The degradation is believed to be caused by imperfect protection of the hydrogen termination layer by the Al_2O_3 dielectric, but further work is needed for confirmation.

Acknowledgements

The authors thank the University of Maryland NanoCenter for equipment and staff support. This effort is sponsored by the U.S. Department of Defense, Defense Threat Reduction Agency (Grant HDTRA1-17-1-0007) and the National Science Foundation (EAGER Grant). The content of this information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred.

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ACRONYMS

FET: Field effect transistor
2DHG: Two-dimensional hole gas
HPHT: High pressure high temperature
AFM: Atomic force microscopy
I-V: Current-voltage
ALD: Atomic layer deposition
V_t: Threshold voltage
$g_{m,max}$: Maximum transconductance
I_{off}: Off-state leakage current
$I_{ds,max}$: Maximum on-state current
R_{on}: On-resistance