Local oxidation of hydrogenated diamond surfaces for device fabrication

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(March 18, 2002)

Abstract

The combination of photolithography, e-beam lithography and atomic force microscopy (AFM) techniques is used for local oxidation of hydrogen terminated surfaces with resolution down to ≈ 10 nm. Lithographic masks are used for treatment in oxygen plasma. In AFM the surface can be oxidized directly by application of a negative bias voltage to the tip. Using the local oxidation, transistor devices are fabricated on a (100) diamond layer, which was hydrogenated in a microwave plasma. Schottky junctions formed at aluminum contacts to hydrogenated surface are studied for comparison. Spatially resolved Kelvin probe experiments are applied to detect the potential variations in the channel or the depletion layers as a function of bias. The results are discussed focusing on current–voltage and capacitance–voltage variations.

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Keywords: hydrogenated diamond, transistor, AFM, surface potentials

I. INTRODUCTION

Diamond is a wide band gap semiconductor with electronic properties that can be varied from insulating to conductive using boron (p–type) or phosphorous (n–type) doping. In addition to the bulk properties a high surface conductivity has been detected on hydrogen terminated diamond surfaces [1]. The hydrogen termination can be obtained by exposing diamond at $500 - 850 ^\circ C$ to a hydrogen plasma. The C–H dipole at the surface induces the negative electron affinity [2]. Recently, the surface conductivity was shown to be strongly affected by atmospheric adsorbates [3]. It was proposed that due to out–diffusion of electrons into the adsorbate layer a hole accumulation in the valence band is generated, giving rise to high p–type conductivity. In contrast to high conductivity of hydrogenated diamond surface, surface terminated by oxygen is strongly resistive. Thus in–plane electronic devices could be realized by microscopic control of surface termination [4].

In this paper, we present the combined use of photolithography, e–beam lithography and atomic force microscopy (AFM) techniques for local oxidation of hydrogen terminated surfaces with resolution down to $\approx 10$ nm. By use of these techniques, transistor devices are fabricated. Variations of surface potential in the transistor channel as a function of gate bias voltage are investigated by spatially resolved Kelvin probe experiments.

II. EXPERIMENTAL

Device structures were fabricated on a (100) diamond layer, which was hydrogenated for 30 minutes in a microwave plasma at 40 Torr, 800 W, and temperature of 850 ºC.

The fabrication process is illustrated by Fig. 1. Separate hydrogen terminated pattern has been realized by oxygen plasma treatment through photolithographic mask. Gold contacts (ohmic) were then evaporated on source, drain, and gates. Transistor channel was defined by two parallel oxidized lines, which were prepared by e–beam lithography and subsequent
oxygen plasma treatment. Isolation of the gates was finalized by local oxidation in AFM. The 
depletion regions formed at junctions between hydrogenated and oxygen terminated parts 
of surface were biased by the gates to modulate the transistor channel. For comparison, 
aluminum Schottky contacts were evaporated in another part of the sample.

Geometric properties of resulting devices were characterized by AFM. Variations of sur-
face potential in the devices were characterized by images of contact potential difference
(CPD), acquired by lift–mode technique of Kelvin probe microscopy (KPM) [5].

III. RESULTS AND DISCUSSION

Structures as small as \( \approx 100 \) nm could be realized by the e–beam lithography. Fig. 2 shows the lithographic mask where the width of lines is about 200 nm and the width of the channel in the narrowest part is only 80 nm. This was achieved by accurate focusing of the electron beam and careful control of illumination dose.

In the particular device, 4 \( \mu \)m wide transistor channel was prepared. Its CPD image measured by KPM is shown in Fig. 3(a). The width of parallel oxidized lines was 500 nm to ensure good isolation of the gates. As indicated by difference in potential the left line is well isolating the gate. The right line is obviously misaligned. Fig. 3(b) shows the same place, after the leakage of the right gate was corrected by direct oxidation in AFM.

Using AFM in contact mode the diamond surface can be oxidized by application of a negative bias voltage to a doped silicon tip, with a resolution of \( \approx 10 \) nm. To test this technology a set of 6 lines was scribed in a sequence from right to left with bias voltage of \(-4, -6, -8, -10, +10, \) and \(-10 \) V. The image of surface morphology in Fig. 4(a) shows that the threshold for structuring can be considered at \(-4 \) V, the line thickness increases with bias voltage, no line is produced when bias polarity is reversed, and the lines prepared by the same bias voltage are well reproduced. The AFM image corresponds very well to the SEM image of secondary electron emission in Fig. 4(b). Dark lines of various thickness are displayed on a bright background. The bright area is attributed to the negative electron
affinity of hydrogenated surface whereas the dark color of the lines indicate oxidized surface with modified electron affinity.

Note that bias assisted AFM oxidation is accompanied by a change in surface flatness. Recently, a material growth induced by AFM on the diamond surface was reported [4]. Here, the designed pattern was scribed into the surface. This effect is especially pronounced on a square pattern shown in Fig. 5. Average depth of the structure was \( \approx 3.4 \) nm, width of the line at half maximum was \( \approx 40 \) nm. It is worth to emphasize that common silicon tip was used in this procedure.

The resulting transistor device was characterized by profiles of surface potential across the channel. The profiles as a function of gate bias voltage are displayed in Fig. 6(a). Profile of surface height at the same place is shown in Fig. 6(b). The profile of surface potential resolves clearly hydrogenated regions and oxidized lines. At zero bias on the gates the contrast in CPD is given by difference in electron affinity of 1.7 eV due to C–H surface dipole as well as different Fermi level at hydrogen (0.7 eV below valence band minimum [6]) and oxygen terminated surface (in band gap). Equilibrium between the Fermi levels results in depletion of holes from surroundings of oxidized patterns.

Flat potential profile within the channel indicates that the channel is either fully depleted at zero bias or that depletion regions are very narrow. Detection of potential profile across the channel as a function of gate bias can elucidate this. If the channel was already fully depleted, a negative bias on the gates would open the channel and render depletion regions on either side of oxidized line more pronounced.

However, Fig. 6(a) demonstrates that no depletions regions become visible up to \(-10\) V of gate bias voltage. The potential remains more or less flat, suggesting that the depletion must be rather confined to close vicinity of oxidized lines (\( \approx 100 \) nm). Measurements of current–voltage characteristics through the channel as a function of gate bias corroborate this conclusion. More than 50 V was required to significantly modulate the channel current [7]. Note that application of such high voltages in KPM is problematic because resulting electrostatic forces strongly affect the dynamic properties of a cantilever and a contact.
potential difference is out of range of KPM feedback control.

For comparison, the profiles of surface potential across the Schottky junction as a function of reverse bias voltage are displayed in Fig. 7(a). Profile of surface height at the same place is shown in Fig. 7(b). Note an effect of different work function of aluminum (4.2 eV) and hydrogenated diamond (4.9 eV) on a contrast in CPD at zero bias voltage.

The potential on diamond decays across several micrometers from the contact edge. The variation as a function of bias would indicate a wide depletion region. However, the potential profile as measured by KPM is given not only by band bending in the depletion region but also by edge transfer function [5]. Compared to KPM on relatively flat oxidized patterns, the contribution of the transfer function is more pronounced here due to the contact edge.

In addition, a region at the very contact edge may be inaccessible for measurement because of AFM tip shape and height of the aluminum contact. The width of the inaccessible region $x$ can be estimated from geometry by $x = h \tan(\alpha/2)$. Substituting $h = 45$ nm for height at the contact edge and $\alpha = 50^\circ$ for opening angle of the tip apex gives the region width of $x = 21$ nm.

Since evaluation of capacitance–voltage characteristics suggests that a depletion region width of aluminum Schottky junction is in the range of $5 - 50$ nm [7], the depletion regions at Schottky junction are difficult to deduce from the presented potential profiles.

IV. SUMMARY

To summarize, lithographic and AFM techniques were presented and applied to define an operational transistor device on hydrogen terminated diamond surface. Device structures down to $\approx 10$ nm were shown. Hydrogenated as well as oxidized regions were clearly revealed due to their different work functions. Potential profiles across the device junctions as a function of bias indicated narrow depletion regions ($\approx 100$ nm). This was corroborated by current–voltage and capacitance–voltage measurements.
ACKNOWLEDGMENTS

The authors are pleased to acknowledge financial support by the European Community contract HPRN-CT-1999-00139, Deutsche Forschungsgemeinschaft contract NE524-2, and the Procope French-German program.
REFERENCES


FIGURES

FIG. 1. Design of a transistor device. Photolithography, e–beam lithography and atomic force microscopy (AFM) were combined to fabricate the device.

FIG. 2. Image of photoresist layer with developed e-beam structure in AFM. The section of AFM image shows e–beam lines 200 nm wide and the channel as narrow as 80 nm.

FIG. 3. KPM image of the 4 μm wide transistor channel: (a) After e–beam lithography, the right gate is leaking. (b) The leak was corrected by direct oxidation in AFM.

FIG. 4. Local oxidation of diamond in contact AFM using various bias voltages. The oxidized pattern is reproduced in (a) AFM surface morphology and (b) SEM image of secondary electron emission.

FIG. 5. Morphology of a pattern scribed into a diamond surface using negatively biased silicon tip in AFM.

FIG. 6. Spatially resolved potential profile across the transistor channel as a function of gate bias voltage.

FIG. 7. Spatially resolved potential profile across the Schottky junction as a function of gate bias voltage.
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Fig. 3, Rezek

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Fig. 5, Rezek

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Fig. 6, Rezek

(a) Contact potential difference [V] vs. distance [µm] for various gate voltages. (b) Height [nm] vs. distance [µm].

Fig. 7, Rezek

(a) Contact potential difference [V] vs. distance [µm] for aluminum and hydrogenated diamond contacts. (b) Height [nm] vs. distance [µm].