Available online at www.sciencedirect.com

Diamond & Related Materials 15 (2006) 1378 – 1382

DIAMOND AND RELATED MATERIALS

www.elsevier.com/locate/diamond

Depth profiles of the Fermi level at an amorphous-carbon nitride/SiO_2/n-type-Si heterojunction interface obtained by Kelvin probe force microscopy

Takahiro Ishizaki [a],*, Nagahiro Saito [b], Riichiro Ohta [c], Osamu Takai [a]

[a] *EcoTopia Science Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*
[b] *Department of Molecular Design and Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*
[c] *Department of Materials, Physics and Energy Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa, Nagoya 464-8603, Japan*

Received 5 March 2005; received in revised form 9 September 2005; accepted 10 October 2005
Available online 20 December 2005

Abstract

To explore the work function of a typical amorphous-CN film containing a nitrogen concentration of 23.5 at.%, surface potential images were acquired using Kelvin probe force microscopy. Based on the Fermi level of the n-type Si and the contact potential difference between the amorphous-CN film and the n-Si substrate, the work function of the amorphous-CN film was estimated to be 5.2 ± 0.2 eV below its vacuum level. Using the surface potential depth profile for an etched amorphous-CN film, energy diagrams of the amorphous-CN/SiO_2/n-Si interface were constructed based on the positional relationship of the Fermi level. These band diagrams showed that band bending occurred at the amorphous-CN/SiO_2/n-Si interface despite the Fermi level pinning effect of surface trapping due to the SiO_2 insulator layer.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Amorphous-carbon nitride; Kelvin probe force microscopy; Work function

Nitrogen-doped amorphous carbon (amorphous-CN) [1,2] is expected to be applied as an electron field emitter [3–6] and low dielectric constant [7,8] material. In the evolving field of such electronic devices, combined structures composed of a metal/semiconductor and/or an n-type/p-type semiconductor, which have demonstrated a remarkable effect on the performance of electronic materials, have been successfully employed as semiconductor devices. It is therefore critical to consider the electron transport at the heterojunction interfaces since it essentially governs the fundamental performance of such devices. The accurate characterization and interpretation of band diagrams, particularly at these interfaces, is of crucial importance in the evaluation and design of device structure. To achieve this, it is vital to measure the work function at heterojunction interfaces, since the Fermi level depends on doping levels, space charge regions and free carrier concentrations [9]. Since the contact potential difference (CPD) between two materials depends on the work function, CPD measurement can be used to obtain the work function. A common method to measure CPD is the vibrating capacitor or Kelvin method [10]. The Kelvin method provides high sensitivity for potential measurement, but integrates over the entire plate area and does not provide a lateral image of CPD variation on the sample surface [11]. Kelvin probe force microscopy (KPFM) is a powerful tool with high lateral resolution for CPD measurement locally on a surface, since it can image two-dimensional profiles of the difference in the work function of materials and reflect local impurity distribution. Rezek et al. [12] reported that, through surface contact potential images referenced to gold or aluminum pads, the Fermi level of hydrogen-terminated diamond surfaces was deduced to be 0.7 ± 0.1 eV below the valence band maximum.

This paper describes research wherein we employed a Kelvin probe force microscope as a measurement tool to evaluate the work function of a typical amorphous-CN/SiO_2/n-Si heterojunction interface. Attained through detailed analysis of X-ray photoemission spectroscopy and KPFM measurements, we also show energy band diagrams of the amorphous-CN/SiO_2/n-Si interface, wherein band bending occurred due to

---

* Corresponding author. Tel.: +81 52 789 5274; fax: +81 52 789 5235.
E-mail address: ishizaki@plasma.numse.nagoya-u.ac.jp (T. Ishizaki).

0925-9635/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.diamond.2005.10.001

the conservation of thermal equilibrium, based on the positional relationship between the Fermi level and the valence band maximum.

Amorphous-CN film was deposited by shielded arc ion plating (SAIP) under the following conditions [13]. A 64-mm-wide, 32-mm-thick sintered graphite target (Tokyo Tanso, IG510, ash/incombustible impurities 10 ppm) was mounted on a target holder and used as cathode. P-doped n-type Si(100) wafers with a resistivity of 8–12 Ω cm corresponding to a phosphorus concentration of 4.0×10^{15} cm^{-3} were used as substrates. The substrates were sonically cleaned with ethanol twice for 10 min and dried with nitrogen gas. Prior to film deposition, the chamber's pressure was lowered to 1.0×10^{-3} Pa and then it was filled with nitrogen gas to maintain 1 Pa. During the deposition, substrate bias voltage was applied at −100 V and the cathodic arc current was kept at 60 A. Film thickness was regulated to be approximately 70 nm. The chemical composition of the amorphous-CN film was measured by an X-ray photoemission spectroscope (XPS, Shimadzu-Kratos, AXIS) with MgK$_a$ radiation, operating at 10 mA and 12 kV. The analyzer chamber vacuum was 10^{-8} Pa. Charge correction was calibrated using the gold 4f7/2 binding energy. The nitrogen concentration of the film was estimated from XPS measurements to be 23.5 at.%. Band-edge photoemission spectrum measurement of the amorphous-CN film was also performed using XPS with monochromatized AlK$_a$ radiation. CPD images were acquired in a nitrogen atmosphere with a KPFM (Seiko Instruments Inc., SPA-300HV+SPI-3800N) using a gold-coated silicon cantilever with a resonant frequency of 27.5 kHz. An ac bias voltage of 2 V at a frequency of 25 kHz was applied between the sample and the probe. KPFM images of the sample surface were acquired at a probe scan rate of 0.2 Hz. Prior to KPFM measurement, the chamber was evacuated down to ca. 10^{-4} Pa and filled with nitrogen gas. We conducted focused ion beam (FIB) etching with a Ga$^+$FIB system (JEOL, JFIB-2300). A 30-keV Ga$^+$FIB with a beam diameter of 110 nm and beam current of 320 μA was used to etch a square-shaped region of the amorphous-CN film on the sample surface (Si substrate).

Fig. 1(a) shows a CPD image of the amorphous-CN film as referenced to the n-Si substrate. To expose the n-Si substrate, we etched a 10 × 10-μm^2 square-shaped region of amorphous-CN film down 100 nm to a depth of 30 nm below the n-Si substrate surface using the FIB apparatus. The dark and bright regions correspond to low and high surface potential, respectively. The CPD between the amorphous-CN and the n-Si is described as [14]

$$V_{\mathrm{CPD}} = -\{\phi(\alpha) - \phi(\beta)\}/e \tag{1}$$

where $\phi(i)$ and e are the work function of component i and the proton charge, respectively. The surface potential for the as-deposited amorphous-CN film was ca. 420 mV more negative than that of the n-Si substrate. This indicates that the amorphous-CN film had a higher work function than the n-Si substrate. However, these results cannot be interpreted in terms of absolute Fermi level, since the Fermi level for the n-type silicon reference increased to higher than that of intrinsic silicon due to the phosphorus doping. In order to estimate the absolute work function difference between the vacuum level and the Fermi level for the amorphous-CN film, the Fermi level of the n-Si substrate was calculated using the impurity carrier density of 4.0×10^{15} cm^{-3}. The intrinsic carrier density n_{i} is described as

$$n_{\mathrm{I}}^2 = N_{\mathrm{C}} N_{\mathrm{V}} \exp(-E_{\mathrm{g}}/kT) \tag{2}$$

where N_{C} and N_{V} are the effective density of the states in the conduction band and the valence band, respectively, k is the Boltzmann's constant, and T is the absolute temperature. The electron density n is represented as follows

$$n = N_{\mathrm{C}} \exp\{-(E_{\mathrm{C}} - E_{\mathrm{F}})/kT\} \tag{3}$$

or

$$n = n_{\mathrm{i}} \exp\{(E_{\mathrm{F}} - E_{\mathrm{i}})/kT\} \tag{4}$$

where E_{i}, E_{F} and E_{C} are the intrinsic Fermi energy, the Fermi energy and the energy for the bottom of the conduction band, respectively. Assuming the band gap energy, E_{g}=1.1 eV, and the intrinsic carrier density, n_{i}=1.5 × 1010 cm^{-3}, for intrinsic silicon [15], the value of $E_{\mathrm{F}} - E_{\mathrm{i}}$ is ca. 0.32 eV. Considering the effective electron and hole mass for silicon, the Fermi level for intrinsic silicon is approximately 0.013 eV higher than the gap center. Based on these results and the work function of 4.9 eV for intrinsic silicon, we obtained an estimate of ca. 5.0 eV below the vacuum level for the Fermi level of the as-deposited amorphous-CN film surface. However, this obtained value could contain some error, since the n-Si surface etched by the FIB is most likely different from that of the bulk n-Si. This value also includes assumptions made in the calculations and, in addition, may be affected by surface adsorbates. In consideration of this, we measured the contact potential difference between amorphous-CN film and platinum (Pt) by the following procedure. First, Pt with a thickness of 20 nm was deposited on the n-Si by sputtering. Next, an amorphous-CN film was deposited onto the Pt/n-Si substrate. To expose the Pt surface, we etched a 10 × 10-μm^2 square-shaped region of the amorphous-CN film down 80 nm to a depth of 10 nm below the Pt surface using the FIB apparatus. The surface potential for the as-deposited amorphous-CN film was ca. 250 mV more negative than that of the Pt surface. The work function of Pt is known to be 5.6–5.7 eV [16]. Based on the CPD and the reference value of Pt, we obtained an estimate of ca. 5.2 ± 0.2eV below the vacuum level for the Fermi level of the as-deposited amorphous-CN film surface. The difference between the calculated and measured values was ca. 0.3 eV. This difference may be due to damage to the n-Si substrate surface or to additional surface adsorbates originating from the FIB etching [17,18], either of which may have changed the surface Fermi level position. Assumptions made in the calculations may also account for the difference.

In order to investigate the CPD at the heterojunction interface, that is, the amorphous-CN/SiO$_2$/n-Si interface, KPFM measurements were conducted while progressively etching the amorphous-CN film. Fig. 1(b) shows a schematic diagram of our

Download English Version:

https://daneshyari.com/en/article/703180

Download Persian Version:

https://daneshyari.com/article/703180

Daneshyari.com