Hydrogen Depth Profiles at CVD Diamond Surfaces

A. Bergmaier, G. Dollinger, S. Karsch, P. Gluche [a], and E. Kohn [a]

[a] Uni Ulm, Abt. Elektronische Bauelemente und Schaltungen, Albert-Einstein-Allee 45, 89069 Ulm

High performance field effect transistors can be successfully processed from as-deposited diamond films prepared by chemical vapour deposition (CVD) with a highly conductive p-type layer near the surface [1]. The relevance of hydrogen to this conductivity is reported by different authors (e.g. [2]), however, the origin of the high conductive layer is not yet understood. So far, several conduction models of hydrogenated diamond films have been proposed. E.g. it was proposed that the high conductivity layer is due to the passivation of deep levels [3] or that it is attributed to holes generated by shallow acceptor levels [4] related to incorporated hydrogen near the surface. The latter model for the existence of acceptor levels in the subsurface region was also proposed due to hall measurements and was confirmed by secondary ion mass spectroscopy (SIMS) depth profiling, which should support the existence of a hydrogen rich subsurface region [5]. On the other hand it was reported on the basis of scanning tunneling spectroscopy (STS) results that the surface of as-deposited diamond films is hydrogen terminated making the surface negatively charged. Therefore, it was suggested that the negative charge induces a hole accumulation layer near the surface, causing surface band bending and high conductivity due to hole accumulation at the bent band [6].

However, there is still lack of knowledge on the amount of hydrogen incorporated in the bulk and in the subsurface region as well as the amount of hydrogen located on the surface of CVD diamond films. SIMS hydrogen depth profiles as e.g. reported in ref. [5] seem to be meaningless since SIMS is not a suitable technique for hydrogen depth profile analysis in the surface region of diamond films, because it is neither quantitative nor depth resolving in the necessary dimensions. Therefore, high resolution ERD (elastic recoil detection) using heavy ions was employed in order to achieve significant data of hydrogen in and on diamond films. As it was shown in refs. [7,8] heavy ion ERD reveals quantitative results of light impurities in CVD diamond.

Diamond films used in this study were epitaxially grown by microwave plasma CVD on synthetic Ib single crystal diamond (100) substrates at 595°C, using 1.5% CH_4 diluted in hydrogen [1]. After deposition, the samples are kept in the hydrogen plasma for another 10 min without methane, in order to ensure surface hydrogenation and to avoid formation of other carbon species on the sample surface. Since ERD analysis can not be performed in situ, it is likely to contamine the sample surfaces with hydrogen containig molecules, e.g. hydrocarbons, when handling the samples in air before measuring. Wrong results can be obtained, if there is no possibility to distinguish between hydrogen deposited by the reactor process and hydrogen from surface contaminations. In order to avoid ambiguities, growth and termination of the diamond films were carried out using deuterium gas (D_2) instead of H_2.

The diamond films were investigated for their deuterium and hydrogen content with the arrangement for ERD analysis at the Q3D magnetic spectrograph. With this arrangement, the deuterium depth profiles were measured with a depth resolution of about 0.5 nm.

The as-deposited CVD diamond films show a highly conductive layer near the surface as mentioned above. Fig. 1 shows the deuterium depth profile near the surface of the as-deposited film, revealing $(1.70 \pm 0.2) \times 10^{15}$ at/cm^2 of deuterium at the sample surface. Within the errors this value is consistent with a deuterium terminated, (2×1) reconstructed (100) surface, which has a coverage of 1.57×10^{15} at/cm^2. The fwhm of the surface deuterium peak corresponds to a diamond thickness of about 0.5 nm ($\varrho = 3.54$g/cm^3 was assumed for depth calibration), which was the depth resolution of the experimental arrangement in this case. A deuterium and hydrogen bulk content of about 1.0×10^{19} at/cm^3 is measured for depths larger than 1.5 nm, revealing only minor additional hydrogen incorporation below the surface layer. However, this value corresponds well with carrier concentrations measured in many surface conductivity reports [6].

After treatment of the deuterium terminated CVD diamonds in an oxygen plasma for 15 min, the diamond films show a strongly insulating behavior. No deuterium could be found on the diamond surfaces ($< 1 \times 10^{13}$ at/cm^2), whereas an oxygen coverage of $(1.4 \pm 0.3) \times 10^{15}$ at/cm^2 was detected. As expected, the hydrogen bulk concentration near the surface is not affected by the hydrogen plasma treatment and is still at about 1.0×10^{19} at/cm^3.

Concerning our new results, the conduction models of hydrogenated diamond films as reported in refs. [3–5], which are all based on the existence of a hydrogen rich subsurface region, can not be supported. Therefore, the subsurface p-type conduction layer can only be a result of a pure surface hydrogenation, e.g. as proposed by the model of Kawarada *et al.* [6].

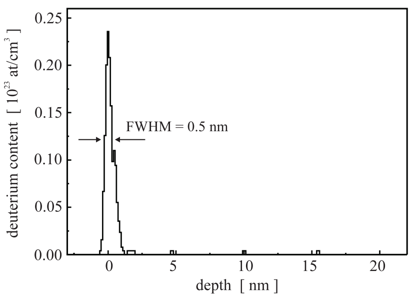

Fig. 1: High resolution depth profile of a deuterated (100) oriented diamond film

References

[1] P. Gluche *et al.*, IEEE Elec. Device Lett., Nov. 1997, in press.
[2] H. Kawarada, Surface Science Reports **26** (1996) 205.
[3] M. I. Landstrass *et al.*, Appl. Phys. Lett. **55** (1989) 1391
[4] T. Maki *et al.*, Jpn. J. Appl. Phys. 1 **31** (1992) L1446
[5] K. Hayashi *et al.*, J. Appl. Phys. **81** (1997) 744
[6] H. Kawarada *et al.*, Phys. Rev. **B52** (1995) 11351
[7] G. Dollinger *et al.*, Diamond Relat. Mater. **4** (1995) 591
[8] A. Bergmaier *et al.*, Diamond Relat. Mater. **5** (1996) 995
[9] G. Dollinger *et al.*, Fres. J. Anal. Chem. **353** (1995) 311