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Very high frequency SAW devices based on nanocrystalline diamond and aluminum nitride layered structure achieved using e-beam lithography

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Abstract

Very high frequency surface acoustic wave (SAW) devices based on the AlN/diamond layered structure are fabricated by direct writing using e-beam lithography on the nucleation side of nanocrystalline diamond (NCD) films deposited by microwave plasma assisted chemical vapor deposition process. The NCD nucleation side is characterized from the point of view of microstructure, morphology and surface topography. Surface roughness as low as 6 nm is reached, which enhances the deposition of AlN film on this flat surface. The interdigital transducers IDTs made in aluminum with lateral resolution down to 600 nm are successfully patterned on the AlN/NCD layered structure with an adapted technological process. Experimental results show that the Rayleigh wave and the higher mode are generated. A high frequency around 4 GHz (mode 1) is obtained for the considered layered structure SAW device, exhibiting a phase velocity of 9200 m/s taking into account the wavelength of 2.4 μm. This value agrees well with calculated values determined from dispersion curves of phase velocity.

Keywords: Nanocrystalline diamond; Surface acoustic wave devices; High frequency electronics; Aluminum nitride

1. Introduction

The increasing demand for large volume data transmission requires larger band-pass surface acoustic wave (SAW) filters operating at high frequency [1]. The high acoustic phase velocity of synthetic diamond makes it very attractive for the achievement of high frequency (GHz range) SAW devices when combined with suitable piezoelectric materials [2]. Among available piezoelectric materials, aluminum nitride is one of the most promising for high frequency SAW devices, owing to its high acoustic phase velocity and its fairly large piezoelectric coupling coefficient along the *c*-axis [3].

Previous studies have demonstrated the feasibility of high-velocity SAW devices based on the AlN/diamond layered structure using either polycrystalline (PCD) or nanocrystalline (NCD) diamond films [4–7]. When PCD films are employed, the synthesis step is generally followed by the implementation of post-treatment techniques aiming to obtain smooth surfaces in order to favor the acoustic wave propagation and to fulfill the requirements of lithographic processes. Even if various polishing methods are now accessible [8], significant developments are still expected in order to facilitate their applications on large area layers and in a cost-efficient manner. In contrast, due to their thickness-independent low surface roughness, NCD films can be used as-grown for the achievement of SAW devices, which represents an interesting alternative to PCD films [9]. Furthermore, the nanometric grain size of such diamond films could help in reducing the important propagation losses usually encountered in polycrystalline structures as a way of improving the device performances [10]. Smooth diamond wafers may also be provided for SAW devices by considering the nucleation side of freestanding polycrystalline layers after removing the silicon substrate by a wet chemical etching [11,12]. In addition to a low surface roughness (≤ 15 nm), the nucleation side is characterized by a relatively small grain size (≤ 300 nm), which can be decreased in the range 40–50 nm by choosing an appropriate nucleation method, hence enhancing the propagation of elastic waves [13]. In the same way, the use of the nucleation side of freestanding NCD layers, usually

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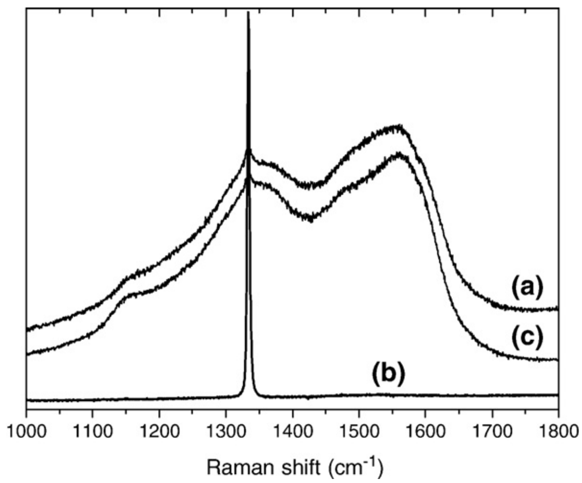

Fig. 1. Raman spectra acquired using a blue laser excitation wavelength (477 nm): (a) nucleation side of freestanding sample; (b) growth side of freestanding sample; (c) growth side of 4 μm-thick NCD film.

characterized by very small grain size below 20 nm [14], could further improve the performances of SAW filters.

As long as the operating frequency of SAW devices is given by $f = V/\lambda$, where V is the phase velocity and λ is the wavelength corresponding to the period of the interdigital transducers (IDTs), very high values of f may be reached by combining in the same time the high phase velocity of diamond and a significant reduction of the IDT period. Devices based on the SiO_2/ZnO/diamond layered structure operating around 5 GHz were thus successfully achieved with conventional lithography [15]. Recently, SAW devices based on the AlN/PCD layered structure operating in the GHz range were realized using electron-beam lithography (EBL), which is one of the most versatile techniques for the fabrication of submicronic and nanometric structures [16]. The achievement of EBL requires very low surface roughness, which could be also well fulfilled by using intrinsically smooth NCD films.

In this paper, we report the fabrication of very high frequency SAW filters based on the AlN/NCD layered structure. Operating frequencies up to 4 GHz are yielded. Both the smooth nucleation side of NCD layers and EBL are considered in order to make possible high lateral resolution of IDTs down to 600 nm.

2. Experimental details

2.1. Diamond film synthesis

The deposition of diamond films was carried out in two steps in order to obtain rapidly the appreciable thicknesses needed for freestanding layers as suggested in [17]. First, the synthesis was initiated during 20 h in a bell jar reactor [7] under conditions promoting NCD. Then the growth was prolonged during 25 h under conditions suitable for PCD in a reactor regularly used for homoepitaxial deposition [18]. (100)-oriented silicon substrates of 1 cm^2 in size were used. Prior to synthesis, the Si substrates were ultrasonically abraded for 1 h in a suspension of diamond powder with a grain size of approximately 45 μm in ethanol. The NCD growth was achieved using a 96% Ar–3% H_2–1% CH_4 feed gas, under 600 W microwave power and 200 hPa pressure, while maintaining the substrate temperature around 1170 K. The PCD growth was then completed using a 96% H_2–4% CH_4 feed gas, under 1700 W microwave power and 120 hPa pressure, keeping the surface temperature at approximately 1070 K. After deposition, the Si substrate was removed by a wet chemical etching in a ($HF:HNO_3$) solution leading to freestanding samples formed of roughly 60 μm of PCD above 20 μm of NCD, with a flat surface on the NCD nucleation side. Furthermore, a 4 μm-thick film was grown in the NCD conditions described above in order to make possible comparisons between the characteristics of its growth side and the nucleation side of freestanding films.

2.2. Aluminum nitride deposition

Smooth piezoelectric AlN films with columnar structure and (002) orientation were deposited on the NCD nucleation side of the freestanding samples by reactive RF magnetron sputtering. The proper deposition parameters for obtaining highly oriented AlN films were optimized in previous work on silicon substrates [19]. For the devices considered in this study, the AlN thickness was set to 1 μm.

2.3. Electron-beam lithography

EBL was used to pattern the IDTs on the AlN/NCD layered structure. Because of the high electrical resistivity of this structure, it is however difficult to develop a pattern due to the

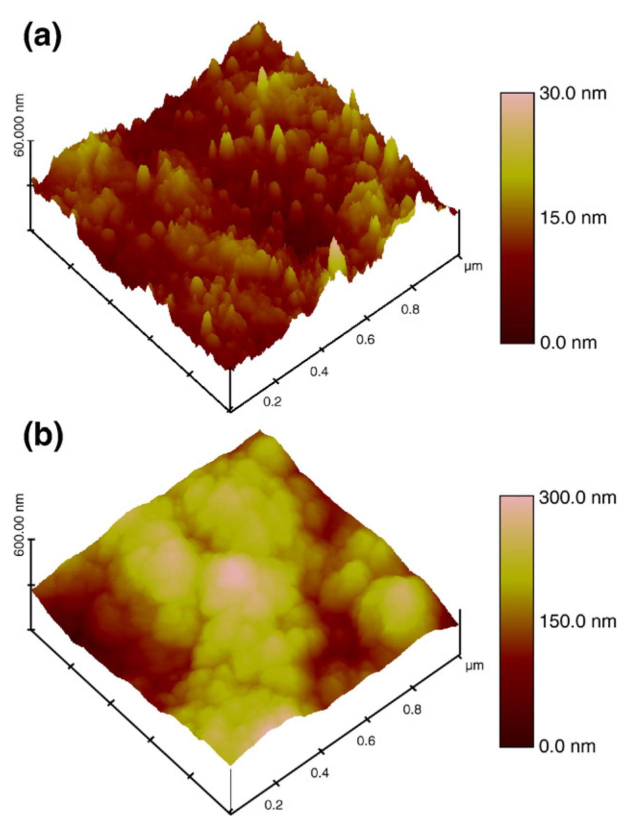

Fig. 2. AFM micrographs obtained on a 1 × 1 μm^2 surface: (a) nucleation side of freestanding sample; (b) growth side of 4 μm-thick NCD film.