Diamond & Related Materials 83 (2018) 118–125

Contents lists available at ScienceDirect

Diamond & Related Materials

journal homepage: www.elsevier.com/locate/diamond

Local probing of the enhanced field electron emission of vertically aligned nitrogen-doped diamond nanorods and their plasma illumination properties

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ARTICLE INFO

Keywords:
Nitrogen-doped diamond nanorods
Reactive ion etching
Field electron emission
Localized emission
Plasma illumination

ABSTRACT

A detailed conductive atomic force microscopic investigation is carried out to directly image the electron emission behavior for nitrogen-doped diamond nanorods (N-DNRs). Localized emission measurements illustrate uniform distribution of high-density electron emission sites from N-DNRs. Emission sites coupled to nano-graphitic phases at the grain boundaries facilitate electron transport and thereby enhance field electron emission from N-DNRs, resulting in a device operation at low turn-on fields of 6.23 V/μm, a high current density of 1.94 mA/cm^2 (at an applied field of 11.8 V/μm) and a large field enhancement factor of 3320 with a long life-time stability of 980 min. Moreover, using N-DNRs as cathodes, a microplasma device that can ignite a plasma at a low threshold field of 390 V/mm achieving a high plasma illumination current density of 3.95 mA/cm^2 at an applied voltage of 550 V and a plasma life-time stability for a duration of 433 min was demonstrated.

1. Introduction

Owing to their unique structural and electrical characteristics, diamond nanostructures (DNSs) are widely used in numerous technological applications such as single photon sources [1], field electron emitters [2,3] ultraviolet nanolasers [4] etc. Recently, tuning the electrical properties of DNSs by the introduction of chemical impurities like nitrogen, boron, phosphorus, etc., has received great attention [5–7]. Particularly, the improvement in electrical conductivity and the change in electronic structure due to nitrogen impurities are investigated on the basis of Mott's three-dimensional variable range hopping theory [8] and Efros-Shklovokii-Pollok-Mott variable range hopping conduction theory [9]. It is reported in a recent study that hopping of electrons at the nanographitic grain boundary region could be reasonable for conduction mechanism for nitrogen-doped diamond nanowires [3]. However, there is no direct confirmation for the localization of current conduction channels in DNSs. This lack of information for the electrical conduction pathways hinders the development for DNSs applications in electron emitting devices. A complete understanding of the current conduction mechanism and tracing of the local conductive behavior could be of high interest for the enhancement of their performance for various electron emission devices. However, it remains a challenge for researchers to selectively probe the local current conduction pathways in DNSs.

In this study, we tackle this challenge while keeping the potential applications in mind. Vertically aligned nitrogen-doped diamond nanorods (N-DNRs) were prepared from nitrogen-doped nanocrystalline diamond (N-NCD) films using a reactive ion etching (RIE) process in O_2 plasma. The current conduction pathways in the nanorods were probed by conductive atomic force microscopy (C-AFM). For comparison, the undoped DNRs (U-DNRs) fabricated from undoped nanocrystalline diamond (U-NCD) films were also investigated. The mechanism behind the enhanced FEE properties of N-DNRs as compared to U-DNRs is elucidated. We observed that the key factor responsible for the

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https://doi.org/10.1016/j.diamond.2018.02.005
Received 11 January 2018; Received in revised form 30 January 2018; Accepted 6 February 2018
Available online 07 February 2018

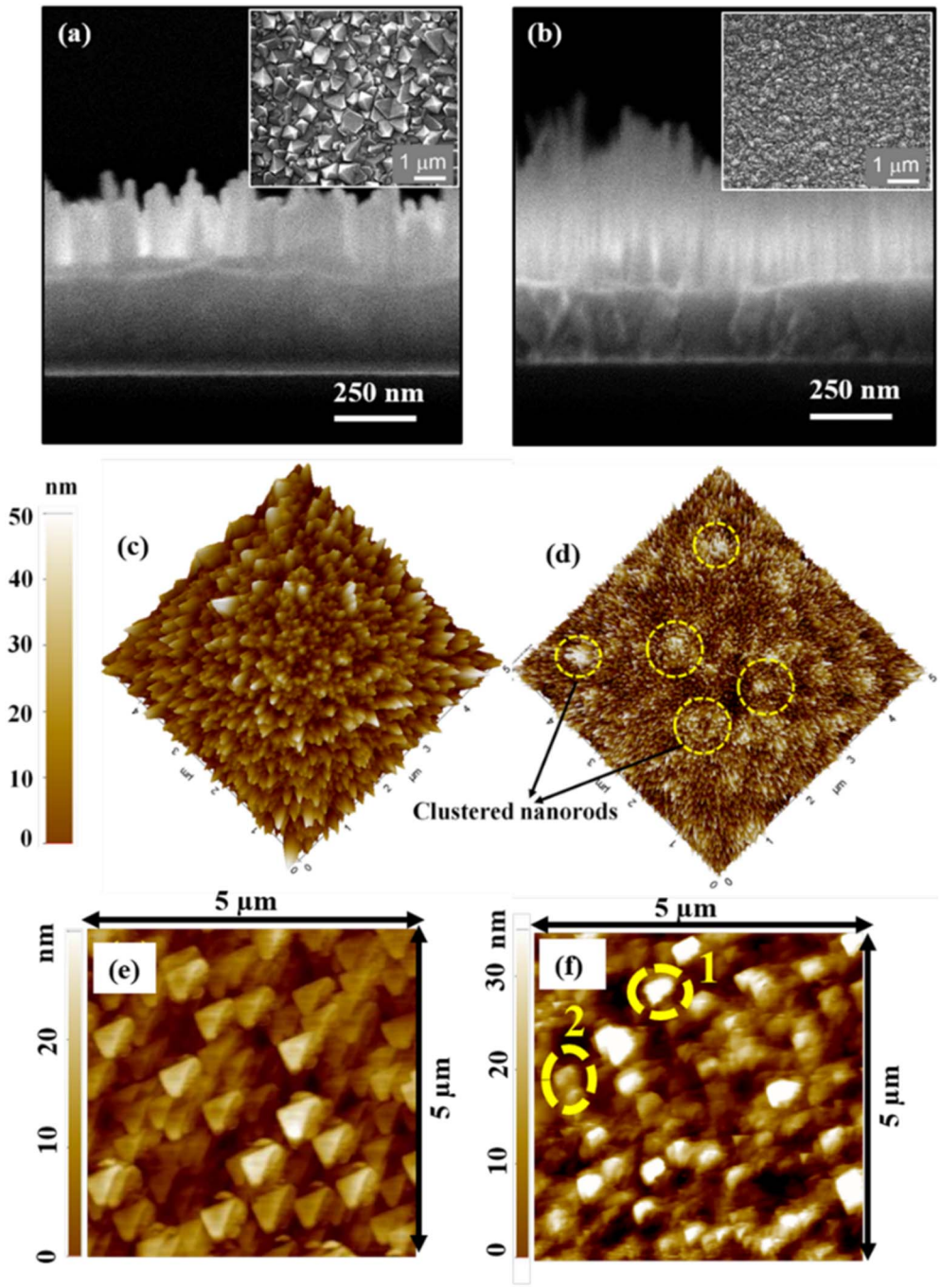

Fig. 1. Cross-sectional SEM images of (a) U-DNRs and (b) N-DNRs with the SEM morphologies of the corresponding diamond (i.e., U-NCD and N-NCD films) shown as insets. (c, d) atomic force microscopy images (3D surface topography) acquired in non-contact mode and (e, f) enlarged AFM morphological micrograph (i.e., two dimensional topography acquired in contact mode) for (c, e) U-DNRs and (d, f) N-DNRs.

improved FEE properties of N-DNRs is the presence of nanographitic phases existing at the grain boundaries of N-DNRs. Furthermore, the benefit of these N-DNRs with good FEE properties on exciting the Ar plasma in a microplasma device with parallel-plate configuration is demonstrated.

2. Experimental

The U-DNRs and N-DNRs were fabricated by a two-step process. In the first step, U-NCD and N-NCD films were deposited on a cleaned Si surface using an ASTeX 6500 series microwave plasma enhanced chemical vapor deposition system. Prior to the diamond deposition, the Si substrates were nucleated with a water based state-of-the-art colloidal suspension of 5 nm nanodiamond (ND) particles [10]. The U-NCD films were deposited using CH_4(1%)/H_2(99%) plasma and N-NCD films were deposited using CH_4(6%)/H_2(91%)/N_2(3%) plasma under the same microwave power of 3000 W for 5 h. The pressure of the reacting chamber and the gas flow rate for the growth of U-NCD and N-NCD films were also the same, i.e., they were 30 Torr and 300 sccm, respectively. The substrate temperature measured by a single color optical pyrometer was 675 °C for U-NCD films and 540 °C for N-NCD films. In a second step, the pristine U-NCD and N-NCD films were immersed in a colloidal suspension of ND particles (~5 nm) and were sonicated for 10 min. The ND particles adhered on the diamond films act as a mask