

Atomically controlled diamond: homoepitaxy, doping, and surface structures

Norio Tokuda^{1,2,3}, Satoshi Yamsaki^{2,3} and Takao Inokuma^{1,3}

¹ Kanazawa University

Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan

Phone: +81-76-234-4875 E-mail: tokuda@ec.t.kanazawa-u.ac.jp

² Energy Technology Research Institute, AIST

Umezono, Tsukuba, Ibaraki 305-8603, Japan

³ JST, CREST, Japan

Abstract

We have studied about homoepitaxy, doping, and surface structure control of single-crystal diamond for next generation high-power devices, optoelectronic devices, bio/chemical sensors, quantum computing, and so on. Recently, we successfully controlled homoepitaxial diamond growth modes, grew delta-doped diamond films, and formed atomically flat diamond surfaces by plasma-enhanced CVD.

1. Introduction

Carbon is a member of group IV with the least atomic number above silicon. Diamond, of which crystal structure is same with that of silicon, has been expected to be the material of the next-generation high-power, optoelectronic, bio/chemical electronic, quantum computing devices, etc., because of the similarity of an electrical property to silicon in addition to the superior physical properties. However, still many problems are remained for the use of semiconductor devices; e.g. difficulties of growth mode control due to a plasma process, high resistivity at room temperature due to deep dopant levels, surface roughness, etc. Here, we report the determination and control of the homoepitaxial diamond growth modes, the formation of delta-doped diamond films to lower the resistivity, and the formation of atomically flat diamond surfaces.

2. Homoepitaxy

CVD diamond growth needs to be conducted under non-equilibrium conditions because graphite is more stable phase of carbon than diamond under normal conditions. Therefore, hydrogen radicals is necessary to remove non-diamond carbon including graphite formed on the diamond surface during the CVD process. Methane is commonly used as the reactant gas for the CVD diamond growth. CH_x radicals are formed by hydrogen abstraction reaction. And then, the recombination of the methyl radicals induces to form C_2H_y radicals. The CH_x and C_2H_y radicals are regarded as the precursor for diamond growth during CVD process. These radicals play an important role in plasma-enhanced CVD (PECVD) diamond growth, whose mechanism is more complex as compared to that of other semiconductor films conducted by non-plasma processes such as thermal CVD, molecular beam epitaxy, etc.

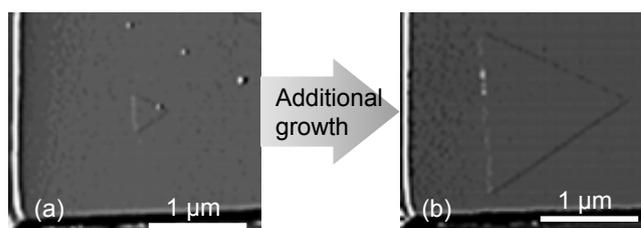


Fig. 1(a) AFM images of diamond (111) surface on the same mesa structure before and (b) after additional growth.

Thus, it is difficult to elucidate the growth mechanism and evaluate the growth modes.

Recently, we reported the evaluation method of homoepitaxial diamond growth modes: lateral growth, two-dimensional (2D) island growth, and three-dimensional growth [1]. Figure 1(a) shows atomic force microscopic (AFM) image of an atomically flat diamond (111) surface with a triangular island formed by 2D island growth. Figure 1(b) shows AFM image of the diamond surface after homoepitaxial lateral growth without 2D terrace nucleation. The equilateral triangular island was enlarged only laterally by the additional homoepitaxial growth. Thus, we can control the homoepitaxial diamond growth modes by PECVD.

3. Delta-doping

Donor and acceptor levels in diamond are deep ($E_D = 0.58$ eV for P, $E_A = 0.37$ eV for B) and thermal activation of free carriers is incomplete at room temperature. To solve the problem, a concept of delta-doping in diamond has been proposed [2] and boron delta-doped diamond structures have been formed and characterized [3, 4]. However, the effective electrical characteristics of delta-doping has not been experimentally achieved yet. To achieve the electrical effect of delta-doping, abrupt interfaces between thin highly boron doped and intrinsic layers requires.

We tried to grow delta-doped diamond films by above-mentioned lateral growth and heavy boron doping techniques. The delta-doped diamond films had the depth profile of boron concentration, consisting of four delta-doped layers with 10^{20} B atoms/cm³ in lowly doped film with 10^{17} B atoms/cm³, as shown in Fig. 2. The result shows that the abrupt doping profile with thin transition layer in the multi delta-doped diamond structure was achieved.

4. Atomically flat surfaces

Surface and interface roughness is one of the most important issues for semiconductor materials in the realization of electronic devices with prospective performance. Many efforts have been expended on flattening surfaces of Si, GaAs, SiC, and GaN in atomic level and then has led to achievement of atomically step-free surfaces [5-8]. The surfaces of as-polished diamond substrates are not atomically flat but has a roughness of several nm or more due to the mechanical polishing.

Recently, we reported the formation of atomically flat diamond (111) surfaces by controlling the homoepitaxial growth modes [1, 9-10]. Figure 3 shows AFM images of three types of diamond (111) surfaces: (a) as-polished surface, (b) atomically flat surface with step/terrace structure, and (c) atomically step-free surface. We also reported the formation of an atomically step-free diamond (111) surface with $100 \times 100 \mu\text{m}^2$ in size [1], which is possible to fabricate device structures, such as Schottky barrier and *pn*-junction diodes, transistors, and so on.

5. Conclusions

We successfully controlled homoepitaxial diamond growth modes, grew delta-doped diamond films, and formed atomically flat diamond surfaces by PECVD. We expect that the realization of diamond electronics is accelerated by the application of these techniques.

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References

- [1] N. Tokuda, T. Makino, T. Inokuma, and S. Yamasaki, *Jpn. J. Appl. Phys.* **51** (2012) 090107.
- [2] A. Denisenko and E. Kohn, *Diamond Relat. Mater.* **14** (2005) 491.
- [3] R. Edgington, S. Sato, Y. Ishiyama, R. Morris, R. B. Jackman, and H. Kawarada, *J. Appl. Phys.* **111** (2012) 033710.
- [4] G. Chicot, T. N. Tran Thi, A. Fiori, F. Jomard, E. Gheeraert, E. Bustrarret, and J. Pernot, *Appl. Phys. Lett.* **101** (2012) 162101.
- [5] D. Lee, J. M. Blakely, T. W. Schroeder, and J. R. Engstrom, *Appl. Phys. Lett.* **78** (2001) 1349.
- [6] T. Nishida and N. Kobayashi, *Appl. Phys. Lett.* **69** (1996) 2549.
- [7] J. A. Powell, P. G. Neudeck, A. J. Trunek, G. M. Beheim, L. G. Matus, R. W. Hoffman, Jr., and L. J. Keys, *Appl. Phys. Lett.* **77** (2000) 1449.
- [8] T. Akasaka, Y. Kobayashi, and M. Kasu: *Appl. Phys. Express* **2** (2009) 091002.
- [9] N. Tokuda, H. Umezawa, S. Ri, M. Ogura, K. Yamabe, H. Okushi, and S. Yamasaki, *Diamond Realt. Mater.* **17** (2008) 1051.
- [10] N. Tokuda, H. Umezawa, K. Yamabe, H. Okushi, and S. Yamasaki, *Diamond Relat. Mater* **19** (2010) 288.

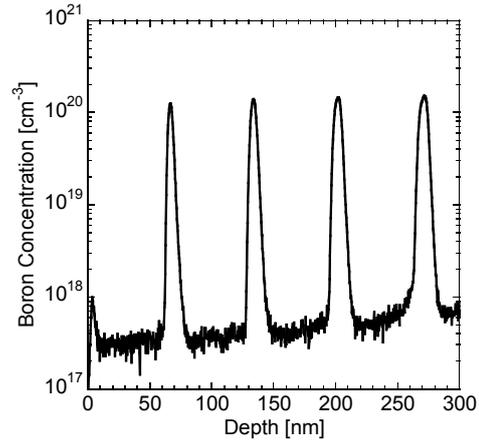


Fig. 2. SIMS depth profile of boron concentration in delta-doped diamond (111) film.

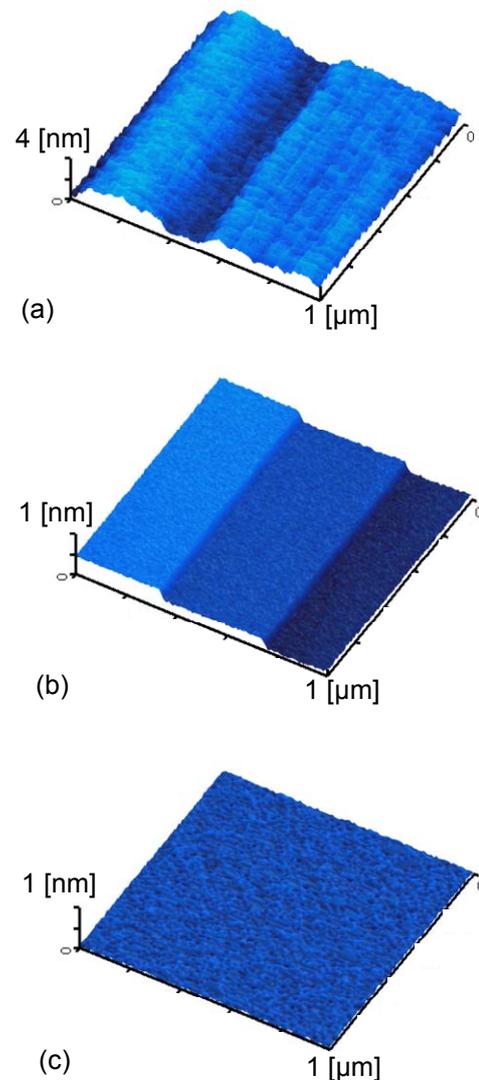


Fig. 3. AFM images of diamond (111) surfaces: (a) as-polished surface, (b) atomically flat surface with step/terrace structure, (c) atomically step-free surface.