

論文 / 著書情報  
Article / Book Information

|                   |                                                                                                                                                                                                 |
|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 題目(和文)            | 高感度磁気センサに向けたダイヤモンドの結晶成長の研究                                                                                                                                                                      |
| Title(English)    | Study of diamond crystal growth for highly sensitive quantum sensors                                                                                                                            |
| 著者(和文)            | 辻起行                                                                                                                                                                                             |
| Author(English)   | Takeyuki Tsuji                                                                                                                                                                                  |
| 出典(和文)            | 学位:博士(工学),<br>学位授与機関:東京工業大学,<br>報告番号:甲第12571号,<br>授与年月日:2023年9月22日,<br>学位の種別:課程博士,<br>審査員:波多野 睦子,宮本 恭幸,若林 整,山田 明,岩崎 孝之,加藤 宙光                                                                    |
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| 学位種別(和文)          | 博士論文                                                                                                                                                                                            |
| Category(English) | Doctoral Thesis                                                                                                                                                                                 |
| 種別(和文)            | 論文要旨                                                                                                                                                                                            |
| Type(English)     | Summary                                                                                                                                                                                         |

## 論文要旨

### THESIS SUMMARY

|                                            |               |          |                                           |                 |      |
|--------------------------------------------|---------------|----------|-------------------------------------------|-----------------|------|
| 系・コース：<br>Department of, Graduate major in | 電気電子<br>エネルギー | 系<br>コース | 申請学位 (専攻分野)：<br>Academic Degree Requested | 博士<br>Doctor of | (工学) |
| 学生氏名：<br>Student's Name                    | 辻 起行          |          | 審査員主査：<br>Chief Examiner                  | 波多野睦子           |      |

### 要旨 (英文 800 語程度)

Thesis Summary (approx.800 English Words)

Nitrogen-vacancy centers in diamond are attracting attention as a next-generation magnetoencephalography (MEG). Unlike existing MEG based on superconducting quantum interference devices (SQUIDs), which only operate at cryogenic temperatures and require a large cooling system, NV centers can operate at room temperature and are expected to significantly reduce the device size of MEG. However, the magnetic sensitivity of NV centers has been  $15 \text{ pT}/\sqrt{\text{Hz}}$ , lower than that of SQUIDs (ranging from  $100$  to  $1 \text{ fT}/\sqrt{\text{Hz}}$ ). Therefore, enhancing the magnetic sensitivity of NV centers to under  $1 \text{ pT}/\sqrt{\text{Hz}}$  is needed for the miniaturization of MEG.

The magnetic sensitivity of NV centers is enhanced by improving the contrast ( $C$ ), number of NV centers ( $N$ ) and spin dephasing time ( $T_2^*$ ). Firstly, controlling the alignment of NV centers is needed to improve  $C$ . NV centers can be aligned in four directions corresponding to the four dangling bonds of carbon atoms and each NV center is sensitive only to the magnetic field component parallel to its orientation axis. Therefore, aligning all NV centers in a single specific direction leads to a four-fold increase in  $C$ . Secondly, increasing the thickness of diamond film can improve  $N$ . Thirdly, mitigating stress distribution in the diamond lattice can improve  $T_2^*$ . NV center can be formed using the Chemical Vapor Deposition (CVD). The advantage of the CVD is the ability to control the alignment of NV centers. However, the challenges of CVD arise from the small diamond film thickness of typically only a few micrometers, as well as the absence of an established method to mitigate stress distribution in the CVD film. To achieve the required magnetic sensitivity for MEG, it is needed to realize diamond film containing aligned NV centers with a thickness of  $100 \text{ }\mu\text{m}$  or more and mitigating stress distribution.

This study focused on enhancing the magnetic sensitivity of NV centers by increasing the thickness and mitigating the stress distribution of diamond films with aligned NV centers using CVD. Firstly, the growth rate of CVD diamond film was improved by introducing high plasma power density CVD. Previous studies had limited the growth rate of step flow growth required for aligned NV centers to  $0.5 \text{ }\mu\text{m}/\text{h}$  or less, resulting in excessively long growth times to achieve film thicknesses of  $100 \text{ }\mu\text{m}$ . This study introduced high plasma power density CVD, which enhanced gas decomposition efficiency. By reflectively concentrating the microwave plasma directly on the diamond substrate with a spherical chamber, the plasma power density in this study was 2.5 times higher than in previous studies, which lead to an increasing growth rate of step-flow growth for  $6.6 \text{ }\mu\text{m}/\text{h}$ . Secondly, the misorientation-angle dependence of NV center characteristics was evaluated. To introduce step-flow growth required for realizing aligned NV centers, the (111) diamond surface needed to be polished at an angle (=misorientation-angle  $\theta_{\text{mis}}$ ) in the  $[112]$  direction. The maximum thickness of the CVD film increases as the  $\theta_{\text{mis}}$  is increased. In this study, the  $\theta_{\text{mis}}$  dependence (ranging from  $0.5^\circ$  to  $10^\circ$ ) of NV center properties was evaluated, revealing that the product of NV center density and  $T_2^*$  was higher at larger  $\theta_{\text{mis}}$ . Thirdly, the stress distribution in the diamond film was mitigated to improve  $T_2^*$ . The  $T_2^*$  of NV centers is primarily limited by electron spin bath around the NV centers and the stress distribution. This study discovered that increasing the  $\theta_{\text{mis}}$  on the diamond substrate from  $2^\circ$  to  $10^\circ$  resulted in a reduction of the stress distribution by more than  $1/10$  and  $T_2^*$  approached its value limited by the electron spin bath. Previous studies showed that stress distribution occurs around dislocations. In this study, the number of dislocations in the CVD film was evaluated by counting the number of etch pits formed when exposing the CVD films to  $\text{H}_2\&\text{O}_2$  plasma. Twenty etch pits were observed in the CVD film on the substrate with  $\theta_{\text{mis}}$  of  $3.3^\circ$ , whereas no etch pits were observed with  $\theta_{\text{mis}}$  of  $10^\circ$ , which demonstrated that the number of dislocations in the CVD film decreased as the  $\theta_{\text{mis}}$  increased. Finally, a thick diamond film containing aligned NV centers with a thickness of  $100 \text{ }\mu\text{m}$  or more was successfully obtained using a  $1 \text{ mm}$  square diamond substrate polished at a high  $\theta_{\text{mis}}$  of  $10^\circ$ .

In conclusion, since these technologies contribute to the fabrication of diamond materials with high magnetic sensitivity, this study pave the way for the miniaturization of MEG.

備考：論文要旨は、和文 2000 字と英文 300 語を 1 部ずつ提出するか、もしくは英文 800 語を 1 部提出してください。

Note: Thesis Summary should be submitted in either a copy of 2000 Japanese Characters and 300 Words (English) or 1copy of 800 Words (English).

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