1. Research Title:

NMR Study on Phosphorus-Doped Silicon Crystal for Application to Quantum Computing

2. Term of Research: From July 1, 2006 To June 30, 2008

3. Total Budget

a. Financial Support by JSPS: Total amount: 2400 thousand yen
   1st Year 1200 thousand yen  2nd Year 1000 thousand yen
   3rd Year 200 thousand yen

b. Other Financial Support: Total amount: 0 thousand yen

4. Project Organization

a. Japanese Principal Researcher

<table>
<thead>
<tr>
<th>Name</th>
<th>Akira Matsubara</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institution / Department</td>
<td>Kyoto University Research Center for Low Temperature and Material Sciences (LTM-Center)</td>
</tr>
<tr>
<td>Position</td>
<td>Associate Professor</td>
</tr>
</tbody>
</table>

b. Korean Principal Researcher

<table>
<thead>
<tr>
<th>Name</th>
<th>Soonchil Lee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institution / Department</td>
<td>Korea Advanced Institute of Science and Technology (KAIST), Department of Physics</td>
</tr>
<tr>
<td>Position</td>
<td>Professor</td>
</tr>
</tbody>
</table>
c. List of Japanese-side Participants (Except for Principal Researcher)

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/Department</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takao Mizusaki</td>
<td>Toyota Physical and Chemical Research Institute (Toyota Institute)</td>
<td>Research Fellow</td>
</tr>
<tr>
<td>Tomohiro Ueno</td>
<td>Kyoto University, Graduate School of Medicine</td>
<td>Assistant Professor</td>
</tr>
<tr>
<td>Yutaka Sasaki</td>
<td>Kyoto University, LTM-Center</td>
<td>Associate Professor</td>
</tr>
<tr>
<td>Kohji Fukuda</td>
<td>Kyoto University, Graduate School of Medicine</td>
<td>Professor</td>
</tr>
<tr>
<td>Meiro Chiba</td>
<td>University of Fukui, Graduate School of Engineering</td>
<td>Professor</td>
</tr>
<tr>
<td>Seitaro Mitsudo</td>
<td>University of Fukui, Research Center for Development of Far-Infrared Region</td>
<td>Professor</td>
</tr>
</tbody>
</table>

d. List of Korean-side Participants (Except for Principal Researcher)

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/Department</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mingee Jeong</td>
<td>KAIST, Department of Physics</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Myeonghun Song</td>
<td>KAIST, Department of Physics</td>
<td>Graduate Student</td>
</tr>
</tbody>
</table>
5. **Number of Exchanges during the Final Fiscal Year**

**a. from Japan to Korea**

<table>
<thead>
<tr>
<th>Name</th>
<th>Home Institution</th>
<th>Duration</th>
<th>Host Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Mizusaki</td>
<td>Toyota Institute</td>
<td>2006.10.23-10.29</td>
<td>KAIST</td>
</tr>
<tr>
<td>Y. Sasaki</td>
<td>Kyoto Univ.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Matsubara</td>
<td>Kyoto Univ.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T. Ueno</td>
<td>Kyoto Univ.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K. Fukuda</td>
<td>Kyoto Univ.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M. Chiba</td>
<td>Univ. of Fukui</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T. Mizusaki</td>
<td>Toyota Institute</td>
<td>2007.05.07-05.11</td>
<td>KAIST</td>
</tr>
<tr>
<td>T. Mizusaki</td>
<td>Toyota Institute</td>
<td>2007.11.12-11.17</td>
<td>KAIST</td>
</tr>
<tr>
<td>M. Chiba</td>
<td>Univ. of Fukui</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. Mitsudo</td>
<td>Univ. of Fukui</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T. Mizusaki</td>
<td>Toyota Institute</td>
<td>2008.05.28-06.03</td>
<td>KAIST</td>
</tr>
</tbody>
</table>

Total: 11 persons

Total: 72 days

**b. from Korea to Japan**

<table>
<thead>
<tr>
<th>Name</th>
<th>Home Institution</th>
<th>Duration</th>
<th>Host Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Jeong</td>
<td>KAIST</td>
<td>2006.09.05-10.17</td>
<td>Kyoto Univ.</td>
</tr>
<tr>
<td>M. Song</td>
<td>&quot;</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>M. Jeong</td>
<td>KAIST</td>
<td>2007.02.14-2.23</td>
<td>&quot;</td>
</tr>
<tr>
<td>M. Song</td>
<td>&quot;</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>M. Jeong</td>
<td>KAIST</td>
<td>2007.05.26-07.25</td>
<td>Kyoto Univ., Univ. of Fukui</td>
</tr>
<tr>
<td>M. Song</td>
<td>&quot;</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>M. Jeong</td>
<td>KAIST</td>
<td>2007.09.16-09.29</td>
<td>Kyoto Univ.</td>
</tr>
<tr>
<td>S. Lee</td>
<td>&quot;</td>
<td></td>
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<tr>
<td>M. Song</td>
<td>KAIST</td>
<td>2008.01.28-02.16</td>
<td>Kyoto Univ., Univ. of Fukui</td>
</tr>
<tr>
<td>M. Jeong</td>
<td>KAIST</td>
<td>2008.07.09-07.20</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Total: 10 persons

Total: 288 man-days
6. Objective of Research

Among various quantum computing architectures, silicon-based nuclear spin system proposed by Kane has been pursued most intensively because of its compatibility with existing Si-based microelectronics. Basic concept of Kane’s quantum computing model is shown in Fig.1, where dopant $^{31}$P nuclear spin with $I=1/2$ in Si serves as a Q-bit. Kane discussed in his mode that in order to make $^{31}$P nuclear spin to serve as a Q-bits, we have to quench electron spin freedom so that Si:P has to be cooled down to 40 mK under 4 T magnetic field.

The $^{31}$P nucleus is located underneath A-Gates and by applying voltage on A-Gate and using Stark effect on the hyperfine interaction between doped electron and $^{31}$P nucleus, we can selectively access the desired Q-bit. The J-Gates can switch on and off the overlap of doped-electron wave function between two adjacent P. During switch-on the J-Gate voltage, Q-bits interact with each other and form an entangled state of the Q-bits and quantum operation takes place in quantum computer. There are still technical difficulties to overcome to use Si:P system for quantum computer such as state-of-art technology of nanofabrication for manipulation of dopant $^{31}$P and for A- and J-Gates and also the read-out of Q-bits.

In this research, we study the basic properties of Si:P samples at very low temperatures and high magnetic fields in insulating samples and metallic samples for application of Si:P for quantum computing. The critical dopant P concentration for metal-insulator transition in Si:P is $3.7 \times 10^{18}/\text{cm}^3$. We took NMR in Kyoto University and ESR in University of Fukui to investigate nuclear spin coherent time, $T_2$ in insulating samples, nuclear spin-lattice constant, $T_1$, which is important time constant to cool down spin system to low temperature at about 40 mK. In metallic samples where the electron wave functions are overlapped with each other, it is very interesting to investigate $T_2$ in the entangled state of Q-bits. The Start effect has been investigated by using X-band ESR from shift of hyperfine resonance under a strong electric field. In order to investigate the Stark effect, the control of sample quality against the E-field breakdown is essential. Through this Japan-Korea joint project, we will clarify the basic properties of Si:P system under high magnetic fields and very low temperatures in order to apply it for quantum computing. We will eventually extend our collaboration to combine three extreme conditions of high magnetic fields, very low
temperatures and high electric fields to apply Si:P for quantum computing.

7. Methodology

As described in the paragraph 6, three institutes (Kyoto University, University of Fukui and KAIST) divided the research targets to investigate basic properties of Si:P system for application of quantum computing as follows:

7-1. NMR research in Kyoto University.

We studied NMR for metallic powder samples with various P-concentrations, $n = 1.8 \times 10^{18}$ cm$^{-3}$ and $4.6 \times 10^{18}$ cm$^{-3}$, at very low temperatures down to 40 mK at high magnetic field of about 8 T. This is the first NMR research taken down to 40 mK at 8 T. We tried to search $^{31}$P-NMR at lower concentrations. But the linewidth is rapidly broadened as the concentration is lowered and no NMR was observed in insulating samples below the critical concentration of $3.6 \times 10^{17}$ cm$^{-3}$ for the metal-insulator transition. We found two new discoveries of the nuclear relaxation process of $T_1$ and $T_2$. During the course of NMR experiment, we found the polarization phonon echoes in an insulating sample with p-concentration $n = 6 \times 10^{17}$ cm$^{-3}$.

7-2. ESR in University of Fukui.

In order to compensate no NMR signal observed in insulating sample, we took cw-ESR in insulating samples with concentration, $n = 2 \times 10^{17}$, $6.5 \times 10^{16}$, $2.8 \times 10^{15}$ cm$^{-3}$ at high fields. ESR frequencies were typically chosen at 80-100 GHz. We focused ESR for a sample with P-dopant concentration of $6.5 \times 10^{16}$ cm$^{-3}$ at 80 GHz between 30 K and 1.5 K by the field-modulation method. This is the first ESR taken for relatively low concentration of P at high fields and low temperatures. We try to extract nuclear spin information from ESR. Anomalously large ESR signal was found below about 15 K.

7-3. Stark Effect on the hyperfine coupling by X-band ESR in KAIST.

Confirmation of the Stark effect on hyperfine resonance frequency is important to apply Si:P for quantum computing by Kane model. In KAIST, electrodes are deposited on the insulating sample. There are two hyperfine states in the insulating samples separated by 42 Gauss in zero E-field. When E-field is applied to the sample, the hyperfine splitting should depend on applied E-field. They applied a large E-field before the electric breakdown of the sample. They have not succeeded in observing reproducible Stark effects yet.