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HAL Id: jpa-00220970
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Submitted on 1 Jan 1981

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ACOUSTIC ATTENUATION BY SHALLOW DONORS IN GERMANIUM IN A MAGNETIC FIELD

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Abstract.- We have reported on the experimental results of the acoustic attenuation at about 1 GHz in antimony doped germanium in a magnetic field and at liquid helium temperatures, and that the magnetic field effect on the acoustic attenuation (MFEAA) is far larger than that expected from the present theories. Further experiments were carried out to measure the MFEAA in n-type (antimony, phosphorous or arsenic doped) germanium in the higher frequency region (2-3 GHz) and in other configurations. Some interesting results were obtained and these are summarized as follows: (1) When the magnetic field H was applied along the [100] axis and the wave vector q and the polarization vector ε were along the [110] axis (in this configuration, the degeneracy of the four-pair conduction band minima in the k-space is not removed, so only the shrinkage effect of the donor wave function is expected as an effect of the magnetic field on the ground states of the bound donor electrons) the attenuation decreased with magnetic field and showed a minimum at 27 kG, then, increased with field up to 60 kG. The position of the minimum point is independent of the donor concentration or of the temperature or of the frequency. Such a behavior can not be explained by the present theories. (2) From the experimental results of MFEAA in phosphorus doped germanium for the configuration of H/q/ε/[111] axis at 3.35 GHz, it was found that the effective Bohr radius a* increases with temperature. (3) From the experimental results of MFEAA in arsenic doped germanium for the configuration of H/q/ε/[111] axis at 3.35 GHz, it was found that the behavior is not explained using a reasonable value for the effective Bohr radius a*.

1. Introduction. It is well known that the V-group (arsenic, phosphorus, antimony) atom in germanium composes shallow donor state, and its ground state is four-fold degenerate, reflecting four equivalent conduction band minima. The valley-orbit interaction and the central cell correction split these degenerate states into the singlet (A₁) and the triplet (T₂). The energy separation between the upper T₂ and the lower A₁ is called valley-orbit splitting and denoted by ΔE, whose values are 4.25(Ge:As), 2.83(Ge:P) and 0.32(Ge:Sb) in unit of meV, respectively. The Interaction between these electrons at ground states are neglected if the concentration of the donor atom n is so small as the condition a*≪R (where, a* *Present address : Department of Physics, University of Lancaster, Lancaster LA1 4YB, U.K.)

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:19815102
is the effective Bohr radius of donor electron, $R = (3/4 \pi n)^{1/2}$ is satisfied. According to the theory of Herring and Vogt (1) for many-valley semiconductors such as germanium, the electrons localized at shallow donor ground state are strongly coupled with the lattice (phonon) through the deformation potential. This effect is observed as a large increase of acoustic attenuation (2,3,4,5) or phonon scattering and their uniaxial stress effect (6). A phenomenological theory for the acoustic attenuation by neutral shallow donor electron was given by Suzuki and Mikoshiba (7), and the quantum mechanical theory was given by Kwok (8).

In order to get more detailed information about the mechanism of acoustic attenuation by neutral shallow donor electrons, MFEAA was measured (4, 5).

From the experimental point of view, MFEAA will give us the absolute value of the attenuation by electronic process, because it can be distinguished from other "attenuations" by dislocations, defects, thermal phonons, mode-conversion at boundaries and/or by the mechanical imperfection of the reflecting faces. From the theoretical point of view, the degeneracy of $T_2$ level is removed by the Zeeman effect and the value of $\epsilon_3$ is changed by the shrinkage of the donor wave function, then, fir detailed information about the interaction between the neutral donor electrons and phonons. We have reported on the experimental results of MFEAA in n-type germanium (3,4,5,9) but the additional interesting types of behavior are found as shown in this report.

2. Experimental Procedure and Technique. A usual pulse echo method was used with the duty time of about 1 micro-second. One of the signal echoes was gated and amplified by the Box-Car Integrator, and then fed to the Y-axis of X-Y recorder. The magnitude of the magnetic field was determined from the magneto-resistance of the search coil wound in the superconducting solenoid, and the output was fed to the X-axis. The temperature was controlled by the manostat during the sweep of the magnetic field, and measured by the carbon calibrated resistor.

Zinc-oxide thin film transducer: A zinc-oxide thin film transducer played an important role in the present experiments because of the following reasons. (a) The stress to the germanium, which is caused by the difference in thermal expansion coefficients between the transducer and germanium, has a large effect on the attenuation (6). This effect was avoided because the thickness of the zinc-oxide film transducer was about 1 micro-meter. (b) The ultrasonic loss by the
bonding was removed because the zinc-oxide thin film transducer was sputtered directly onto the sample after the approximately 1000Å of aluminium electrode was evaporated. (c) Zinc-oxide thin film transducer has a large electro-mechanical coupling constant. (d) This transducer has no magnetic field dependence when the resistivity is sufficiently high. Sample: A single crystal of doped germanium was cut in a cubic of 5x5x5 mm³. The opposing faces were polished in optical flat and parallel to an extent of less than 5 seconds. The concentration of the donor was determined by the Hall coefficient at 7kG and the resistivity by the four-point contact method. The crystallographic axis of the sample was determined by the light figure method using helium-neon gas laser beam with the accuracy of 1 degree. The sample characteristics are shown in Table I.

3. Experimental Results and Discussions. (1) MFEAA in antimony doped germanium for $\mathbf{H}/[100]$, $\mathbf{d}/[\overline{1}0\overline{1}]$ configuration: The experimental results for sample B-7 at 0.83 GHz is shown in Fig.1 and for sample C-3 at 0.84 GHz is shown in Fig.2. The vertical axis shows the change of the acoustic attenuation by the magnetic field (i.e., MFEAA). Fig.3 shows the frequency dependence of the behavior for sample B-7 at 1.6 K, upper curve for 0.83 GHz, lower for 3.35 GHz. From these results, it is summarized as follows: (a) The attenuation coefficient decreases with magnetic field and shows minimum at about 26-27 kG, and then increases. (b) The minimum point is almost independent on the temperature, on the concentration of donor or on the frequency. (c) From the behavior in Fig.1 and 2, the amount of the change of the attenuation coefficient shows a sub-linear dependence to the concentration of donor. In this configuration, the shrinkage of the donor wave function is expected as an effect of the magnetic field on the donor electron at ground state, as a result, the value of the valley orbit-splitting $\Delta$ increases with magnetic field (10). Accordingly, it is expected that the electron population and the life time of the $T_2$ level are reduced, and then the attenuation decreases with magnetic field monotonically. It is apparent that the present results are not explained by the discussions mentioned above. It may be necessary to take into consideration the scattering by such as homo-polar pairs (11). If it is so, this means that there are interactions between the bound donor electrons at low concentration region such as the value of R is about 620 Å (for $n=1.0\times10^{15}/cm^3$). To clarify this problem, further experiments are continued for phosphorus or arsenic doped germanium for $\mathbf{H}/[100]$ configuration.

(2) MFEAA in phosphorus doped germanium for $\mathbf{H}/[\overline{1}0\overline{1}]$ configuration:
The experimental results for sample P-15 at 3.55 GHz for various temperatures are shown in Fig.4, and summarized as follows;

(a) The acoustic attenuation increases with magnetic field and shows maximum, and then decreases at higher fields. (b) MFEA increases with temperatures and shows maximum at 20 K. When the magnetic field is applied along the [111] axis, the degeneracy of the $T_2$ level is removed because the corresponding four-pair of conduction band minima are influenced unequally by the magnetic field. For simplicity, a phenomenological theory in which the Zeeman effect is taken into consideration is used to explain the present results. As an example, one of the best fitted calculated curves using appropriate values for $a^*$ is shown in Fig.4 by the broken line for 20 K, and summarized as follows: The value of the effective Bohr radius $a^*$, which is used as a parameter to fit the theoretical curve to the experimental results, increases with the rising of the temperature, and the obtained values for $a^*$'s are 36, 39 and 40 $\AA$ for 10, 20 and 30 K, respectively. This situation may be due to the fact that as the temperature rises, the probability that the donor electrons stay at higher levels increases, which means the effective Bohr radius increases with the rising temperature. (3) MFEA in arsenic doped germanium for $H//\zeta//\zeta//H$ configuration: The experimental results for sample G-3 at 3.55 GHz are shown in Fig.5, for various temperatures, and summarized as follows. (a) The acoustic attenuation increases with the magnetic field up to 60 kG. (b) The magnitude of MFEA increases with the rising of the temperature and shows maximum at 30 K. To explain this behavior, similar theories as shown in the case of phosphorus doped sample is used, but the fitting of the calculated curves to the experimental can not be obtained by use of reasonable values for $a^*$ such as 30-40 $\AA$.

Acknowledgement. The authors would like to express their deep thanks to Prof. Katsuo Suzuki of Waseda University (Tokyo) for his helpful discussions and encouragement throughout this work.

Fig. 1. Experimental results of MFEAA for sample B-7 at 0.83 GHz. Horizontal axis shows the magnetic field, vertical the change of acoustic attenuation. $\vec{H}/[100]$, $\vec{q}/[\bar{e}]/[\bar{1}70]$.

Fig. 2. Experimental results of MFEAA for sample C-3 at 0.84 GHz. $\vec{H}/[100]$, $\vec{q}/[\bar{e}]/[\bar{1}70]$.

Fig. 3. Frequency dependence of MFEAA for sample B-7 between 0.83 and 3.35 GHz at 1.6 K. $\vec{H}/[100]$, $\vec{q}/[\bar{e}]/[\bar{1}70]$. 
**Fig. 4.** Experimental results of MFEAA for sample P-15 at 3.35 GHz. $\mathbf{H//q//e//[111]}$. Broken line shows a calculated results using 39 $\%$ as a value for $a^*$ at 20 K.

**Table I. Sample Characteristics.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>B-7</th>
<th>C-3</th>
<th>P-15</th>
<th>G-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impurity</td>
<td>Sb</td>
<td>Sb</td>
<td>P</td>
<td>As</td>
</tr>
<tr>
<td>Concentration ($x10^{15}$/cm$^3$)</td>
<td>4.5</td>
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<td>1.1</td>
<td>8.6</td>
</tr>
<tr>
<td>Direction of $\mathbf{q}$</td>
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<td>[110]</td>
<td>[111]</td>
<td>[111]</td>
</tr>
<tr>
<td>Direction of $\mathbf{H}$</td>
<td>[100]</td>
<td>[100]</td>
<td>[111]</td>
<td>[111]</td>
</tr>
</tbody>
</table>