Beta-NMR study of ^{58}Cu in Si

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Cu impurities in Si devices are considered serious contaminants. The short-lived β emitter ^{58}Cu ($I^\pi = 1^+$, $T_{1/2} = 3.2$ s) is attractive for studying the behavior of Cu impurities in Si using the β-NMR technique, which will provide unique information on the mechanism of fast Cu diffusion[1)] or the property of Cu-dopant complex that is related to the gettering technique.[2)] The $N = Z$ odd-odd nucleus ^{58}Cu, consisting of ^{56}Ni plus one proton and one neutron, is also interesting in terms of the nuclear moment, from which we can study the proton-neutron interaction in pf-shell nuclei.[3)]

We detected an NMR signal of ^{58}Cu in Si in 2010, and the magnetic dipole moment $|\mu[^{58}\mathrm{Cu}]| = (0.46 \pm 0.03)\mu_\mathrm{N}$ was obtained.[4)] In 2011, Vingerhoets et al. greatly improved the measurement accuracy using collinear laser spectroscopy, achieving $\mu[^{58}\mathrm{Cu}] = +(0.570 \pm 0.002)\mu_\mathrm{N}$,[5)] which is about 20% larger than ours. One possibility for the discrepancy is the existence of an electric field gradient (EFG) which could be generated if some defects are formed at a ^{58}Cu site in Si, though a cubic symmetry site without EFG is expected in terms of the crystal structure of Si. If the EFG exists, the NMR spectrum should split into two lines with frequencies of $\nu_\pm = \nu_0 \pm \nu_\mathrm{Q}/2$ in the case of $I = 1$, where ν_0 and ν_Q are the carrier frequency and the quadrupole splitting frequency, respectively. In this case, our previous NMR line may have originated from ν_-. In the present study, we have applied the multi-radiofrequency (RF) (β-NQR) technique[6)] to the β-NMR measurement of ^{58}Cu in Si to search for a quadrupole splitting in order to verify the above picture and to solve the discrepancy problem.

The experimental method is similar to our previous one.[4)] Spin-polarized ^{58}Cu nuclei were produced through the charge exchange reaction of ^{58}Ni by impinging a ^{58}Ni primary beam at 63 MeV/u, provided by the RIKEN ring cyclotron with a typical intensity of 100 particle nA, on a 0.5-mm thick Be target. Fully stripped $^{58}\mathrm{Cu}^{29+}$ ions were separated by the RIKEN projectile fragment separator (RIPS) and were implanted into a single crystal sample of B-doped Si at 15 K with the crystal $\langle 001 \rangle$ orientation set parallel to the external magnetic field $B_0 = 0.93$ T, the same condition as in the previous experiment. A pair of resonance frequencies $\nu_\pm$ was searched for by changing both ν_0 and ν_Q, using the β-NQR technique in which two frequencies were applied in series as $\nu_- \rightarrow \nu_+ \rightarrow \nu_-$ during the RF duration to inverse spin polarization of ^{58}Cu.

The resonance was found at ν_0 ~4.1 MHz and ν_Q ~2.6 MHz. The ν_Q spectrum at $\nu_0 = 4.00-4.15$ MHz is shown in Fig. 1, from which $\nu_\mathrm{Q} = 4eqQ/3h(3\cos^2\theta - 1) = (2.6 \pm 0.4)$ MHz was obtained. The EFG q will be obtained using the known Q moment of ^{58}Cu[5)] after determining the angle θ between the main axis of the EFG and B_0 from the crystal orientation dependence of ν_Q. $|\mu[^{58}\mathrm{Cu}]| = (0.58 \pm 0.01)\mu_\mathrm{N}$ was obtained from ν_0, which is in agreement with the data reported by Vingerhoets et al.[5)] The difference between the present $\mu[^{58}\mathrm{Cu}]$ and the previous one[4)] is mostly explained by the quadrupole splitting.

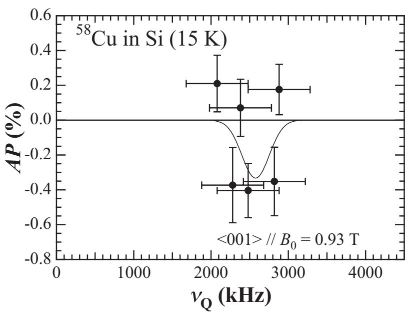

Fig. 1. Beta-NQR spectrum of ^{58}Cu in Si.

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