Behavior of Cu impurity in Si studied by the β-NMR of ^{58}Cu

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Cu impurities in Si devices are known as serious contaminants because of the unique diffusivity of Cu, which is the fastest among transition-metal impurities, enabling them to easily spread over a Si wafer of standard size only in a few hours.[1)] Short-lived β emitter ^{58}Cu ($I^{\pi} = 1^{+}$, $T_{1/2} = 3.2$ s) is an attractive option for a β-NMR probe nucleus for studying the behavior of Cu impurities in Si, which will provide unique information on the mechanism of fast Cu diffusion or the properties of the Cu-dopant complex which is related to the gettering technique.[2)] Using the β-NMR technique, which relies on magnetic dipole moment μ and electric quadrupole moment Q of the probe nucleus, local internal magnetic fields or electric field gradients (EFGs) at a probe nucleus can be observed. In the present case of ^{58}Cu in Si, measurement of the static EFG is essential for examining the structure of a complex such as a B-Cu pair or of off-center substitutional (S) site of implanted Cu ions suggested by β-ray emission channeling.[3)]

We have been performing the ^{58}Cu β-NMR experiments since 2010 using the Riken Projectile Fragment Separator (RIPS) at the RIBF operated by the RIKEN Nishina Center and CNS, University of Tokyo. In previous works, we have shown NMR signals of ^{58}Cu in Si at 15 K in 2010[4)] and signals implying a quadrupole splitting ν_Q, detected in 2013.[5)] In the present study, we have tried to confirm the reproducibility and a beta nuclear quadrupole (β-NQR) spectrum was obtained, as shown in Fig. 1. In the case of ^{58}Cu, which has a nuclear spin $I = 1$, the quadrupole interaction generates a splitting into two NMR lines with frequencies of $\nu_0 \pm \nu_Q/2$, where ν_0 and ν_Q are described as $\nu_0 \simeq \mu B_0/h$ and $\nu_Q = (3/4)eqQ/h(3\cos 2\theta - 1)$, respectively. The spectrum in Fig. 1 was obtained by applying multi RF pulses as a function of ν_Q. Owing to the remarkable progress in the recent μ and Q measurements for ^{58}Cu by laser spectroscopy,[6)] the center frequency ν_0 of approximately 4.04 MHz at B_0 = 0.93 T was estimated, and our result supports the value of $\mu[^{58}\mathrm{Cu}] = +(0.570 \pm 0.002)\mu_N$ in Ref. 6. A ν_Q of approximately 2.5 MHz was obtained from the present ν_Q spectrum. This supports the idea that implanted Cu atoms in the Si lattice are not located in a spatially symmetric configuration, as proposed by the β-ray emission channeling.[3)] The EFG (q) cannot be determined because the angle between the main axis of the EFG and the direction of B_0 is unknown. The EFG for ^{58}Cu in Si is determined from the crystal orientation dependence of ν_Q relative to B_0 and the value of $Q = (15 \pm 3)$ $e$fm^2 in Ref. 6.

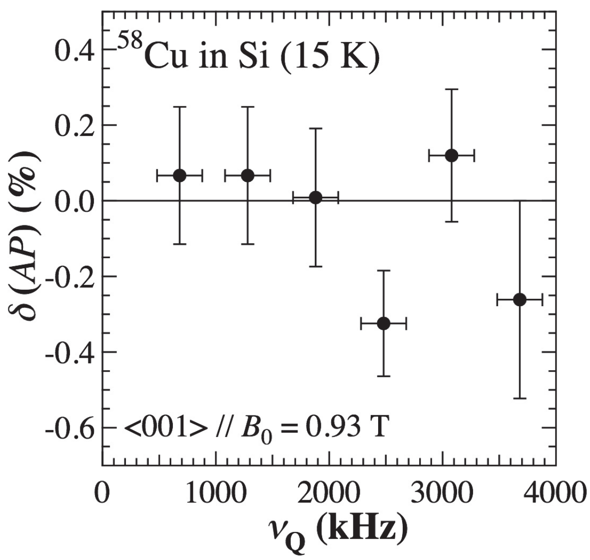

Fig. 1. β-NQR spectrum of ^{58}Cu in Si.

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