Temperature dependence of the lattice constant of Silicon of different isotopic compositions measured by Bragg Backscattering of Synchrotron Radiation

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The lattice constant \( d \) of a crystal depends on its isotopic composition. As pointed out in [1, 2] this is due to the influence of the atomic mass on the zero-point motion. The effect is stronger at low temperatures and is expected to vanish above the Debye temperature. At low temperatures the effect has already been studied for Ge using x-ray standing wave technique with an accuracy of about \( \delta(\Delta d/d) \sim 10^{-5} \) [3]. We studied a layered \( ^{30}\text{Si}/^{28}\text{Si} \) crystal system consisting of a 550 \( \mu \text{m} \) thick \( ^{28}\text{Si} \) single crystal substrate with an about 10 \( \mu \text{m} \) thick epitaxial single crystal layer of \( ^{30}\text{Si} \) on top. The measurements were performed in a backscattering setup using 14.4 keV x-rays at the wiggler beamline BW4 in HASYLAB. The experimental setup is shown in figure 1.

A high-heat-load Si(111) monochromator (M) provided 14.44 keV radiation with \( \simeq 3 \) eV bandwidth. The high energy resolution monochromator (HRM) installed downstream monochromatizes the radiation further to a 7 meV bandwidth. The energy of the radiation is set to the Bragg back-reflection energy for the (12 4 0) reflection in Si, which is 14.438 keV at room temperature. The energy width of the (12 4 0) Bragg backreflection is 6 meV (in a thick crystal) and its energy changes by 1.4 meV if the relative change of the lattice constant \( \delta d/d \) is \( 10^{-7} \). The \( ^{30}\text{Si}/^{28}\text{Si} \) layer is fixed in an oven. A computer controlled temperature stabilization keeps the temperature stable within a few mK [4]. A semitransparent avalanche photo diode (D) with 1 ns time resolution is used to detect backscattered radiation [5]. Energy spectra of (12 4 0) Bragg backreflection at different temperatures in a range between 320 K and 702 K were measured. A typical one is shown in figure 2. To avoid multiple beam scattering effects in Si, the measurements were performed 1 mrad off exact backscattering. The sharp peak at \( E - E_0 = 0 \) is due to the (12 4 0) reflection of the \( ^{28}\text{Si} \) single crystal substrate. The broader peak at \( E - E_0 = 180 \) meV with superimposed oscillations (thickness Pendellösung effect) is the backscattering spectrum of the thin \( ^{30}\text{Si} \) epitaxial layer. The fit, using the dynamical theory, is shown by the solid line. It allows us to determine the difference \( \Delta d \) of the lattice constants in \( ^{30}\text{Si} \) and \( ^{28}\text{Si} \) with a relative accuracy of \( \delta(\Delta d/d) \simeq 2 \times 10^{-7} \). This is...
Figure 2: Backscattering spectra of $^{30}$Si/$^{28}$Si at 678 K

quite precise compared with the accuracy that was achieved for Ge. Figure 3 shows the difference of the lattice constants $\Delta d$ as a function of temperature evaluated from the measured backscattering spectra. At 645 K, the Debye temperature of silicon, the difference $\Delta d$ does not vanish yet, as predicted by the theory. The measurements at higher temperatures are in progress.

Figure 3: Difference of the lattice constants in $^{30}$Si/$^{28}$Si vs temperature

References


