論文内容の要旨

論文題目

Electronic scattering and vibrational excitation on Ge(001) studied by STM

(Ge(001)表面における電子散乱と振動励起の STM による研究)

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Electronic scattering and vibrational excitation are ones of the most fundamental and important phenomena in solid state physics. These are also key factors governing performance of nanoscale devices in nanoelectronics, which is next generation technology. Thus, numerous experiments have been carried out on an elementary process of these phenomena for decades. Two-probe techniques and spectroscopic methods with laser or electron beam irradiation have been widely used for the investigation. However, it is hardly said that the elementary process is well understood at present because these approaches never give information on local structures and local electronic states. Absence of a sample suitable for this purpose also has hindered our understanding, so far.

Electronic scattering and vibrational excitation at surfaces, which can be observed by scanning tunneling microscopy (STM), provide much microscopic information on their elementary process. The STM allows us to directly see the electronic scattering from electronic standing waves in differential conductance (*dI/dV*) images, and atomic structures in topographic images. Scattering potentials can be also obtained by analyzing phase shift of the standing waves. Regarding the vibrational excitation, electron and hole injection from

the STM tip can excite a specific vibrational mode of an individual adsorbate and a local surface structure. Atomic motions due to the vibration can be also seen in the topographic images.

On the clean Ge(001) surface, a quasi-one dimensional electronic system is formed, and electronic standing waves are seen accordingly. Meanwhile, buckling orientation of dimers on this surface is known to be flipped reversibly, remotely, and controllably by electron and hole injection from the STM tip. The Ge(001) surface is, therefore, a unique system where both the electronic scattering and vibrational excitation phenomena emerge. These features can be a great help to discuss, for example, correlation of the electronic scattering with an atomic position or atomic orbitals, and roles of electronic states in the vibrational excitation.

Thus, in the present study, we investigate by STM the electronic scattering and vibrational excitation phenomena on the clean Ge(001) surface and a Ge(001) surface, where a sparse coverage of Sn or Si atoms are deposited.

We first identify the embedded Sn and Si structures on the Ge(001) surface by STM to use them as a template for studying the electronic scattering and the vibrational excitation. We reveal that buckled Sn-Ge and Si-Ge dimers are formed at the substrate Ge dimer position by manipulating the surface dimers by STM at 80 K. Similarly to the Ge dimer, the buckling of these impurity dimers is reversibly flipped, and consequently oppositely-buckled Sn-Ge and Si-Ge dimers are realized. Second, we measure threshold electronic energies for flipping the identified impurity dimers by analyzing surface motion of a topological defect. These energies are examined by the first-principles calculations, and primary physical quantity governing the flip motion is discussed. We indicate that a resonant scattering with spatially-localized electronic state at the topological defect leads to the flipping motion of the Ge and impurity dimers. Third, we investigate the dimer flipping on the bare Ge(001) surface due to the hole injection from the STM tip by tracking the atomic motions in real time. This was done by recording tunneling current variation due to the flip motion with the tip position fixed. We clarify that the flipping motion occurs in a single-hole process, and propose that the hole injection into a backbond of the buckled dimer results in the dimer flipping motion. Finally, we investigate electronic scattering by the identified impurity dimers by measuring electronic standing waves in the *dI/dV* images. Scattering potentials of the impurity dimer are obtained by analyzing phase shift of the observed standing waves. The observed potentials are compared with those obtained by novel but simple calculations. We demonstrate that the scattering potential and the resulting electronic scattering are

systematically changed by atomic species and atomic position.

The findings in the present study described above are expected to improve understanding of the elementary processes of the electronic scattering and the vibrational excitation. They also should provide a platform for the development of nanoelectronics.