Nuclear-spintronics in semiconductors

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Nuclear magnetic resonance (NMR) is widely used in the physical, chemical and biological science. They are also attracted much attention from the viewpoint of quantum computation. However, conventional NMR technique based on induction-detection has a drawback of low-sensitivity and needs a relatively large sample so that it is not suitable to investigate a single layer (or a nanostructure), which is essential for nanotechnologies. In this presentation, I will discuss new possibilities where nuclear spins play an essential role in semiconductor hetero and nanostructures. To overcome low-sensitivity limitation of conventional NMR, we have developed novel NMR technique based on resistance-detection.

Resistance of semiconductor systems is usually determined by the characteristics of carriers and independent of nuclear-spin polarization. However, if we set semiconductor samples to the special situation where different electron-spin states are degenerate, interactions between electron and nuclear spins are enhanced. This interesting situation is realized at ν=2/3 degenerate point in AlGaAs/GaAs system [1-3]. In such situation, nuclear-spin polarization far beyond the thermal equilibrium is realized by current flow (dynamic nuclear-spin polarization) and nuclear-spin polarization can be detected as enhanced resistance, which is proportional to the magnetization, Mz, of nuclear spins [2,4]. This resistance-detection scheme gives us a novel way where nuclear-spin polarization is controlled and detected in a single quantum layer or even in a nanoscale device.

It should be stressed that we need special states at ν=2/3 for dynamic nuclear-spin polarization, but we can apply NMR spectrum and nuclear-spin relaxation (T_1 time) measurements for any states we want to estimate. These measurements were successfully applied to bilayer systems, and exciting phase like canted antiferromagnetic phase was unveiled [5,6]. The low-frequency mode, which is difficult to detect in conventional transport and optical measurements, has been sensitively detected by monitoring T_1, reflecting correlated electron spin features [6].

The nuclear spin control was also extended to a point contact device [4]. From a viewpoint of quantum computation, it is desirable to control small quantity of nuclear spins in small-size solid-state systems. Nuclear spin polarization is realized only in the point contact region and nuclear spin magnetization is detected with the resistance between both ends of the point contact. When an alternating current is applied to the antenna integrated on the point contact, the quantum-mechanic manipulation of Ga and As nuclear spins is achieved by controlling frequency and duration of the applied current pulse. The quantum-mechanic superposition has been successfully manipulated between four separated nuclear-spin states [4]. Full coherent control of quantum four-level system is equivalent to the two-qubit (quantum bit) operation [7]. NMR spectra are also detected with point contact devices and the obtained results are used to analyze population distribution among four nuclear-spin states [8]. The NMR spectra are also helpful to understand strain and spin features at the nanoscale.

In the future semiconductor studies, nuclear spins may play an important role not only as a key player in coherent control but also as a versatile and powerful tool in characterization.

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