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Magnetotransport phenomenon with interacting point-defect system by MBE low-temperature growth

Mohd Ambri Mohamed and Burhanuddin Yeop Majlis

Institute of Microengineering and Nanoelectronics (IMEN),
The National University of Malaysia (UKM)
43600 UKM Bangi, Selangor, Malaysia
Phone: +60-3-8911 8157 E-mail: ambri@ukm.edu.my

Abstract

We study a new possibility of crystal growth as synthesis of materials containing high concentrations of unpaired *sp* electrons by growth of Be doped Gallium Arsenides at low temperatures of 200-300ºC using Molecular Beam Epitaxy (MBE) and investigate a possibility of applications of magnetotransport properties based on these unpaired *sp* electrons to spintronics devices. The present study using high concentration of unpaired *sp* electrons by the growth of Beryllium-doped GaAs layers at low temperatures resulted in a cooperative transition of localized spins at low temperature and affected the mechasnism of tranport properties of the sample. This attempt will give rise to a possibility of adding new functions to existing spintronic devices.

1. Introduction

Semiconductor spintronics is aimed at combining technologies of semiconductor electronics and magnetism for the application of spin transistors and devices for quantum computers. One of the major difficulties in combining these two technologies is caused by the large difference in the impurity concentration between device-used semiconductors and magnetic materials. In this device-used semiconductor such as Si and GaAs, impurity concentrations normally range from 10^{16} cm^{-3} to 10^{19} cm^{-3}, while, in magnetic materials such as metal alloys and oxides, concentrations of magnetic impurities range from the upper part of 10^{20} cm^{-3} to 10^{21} cm^{-3} [1]. This difference is partly due to the difference in the solubility of materials. The disparity in impurities concentration in these two technologies creates a bottleneck to integrate semiconductor electronics and magnetism for the formation of spintronics devices.

There are two types of unpaired electrons in solid materials. The first types are those in magnetic atoms with incomplete *d* or *f* shells and are considered as "atomically built-in unpaired electrons". The other type is unpaired *sp* electrons which form because of broken chemical bonds at surfaces and crystalline defects. The former type of unpaired *d* and *f* electrons give rise to many important properties for applications such as almost all magnetic phenomena and catalytic reactions at solid surfaces. The study of this magnetic system is well established. The latter type of unpaired electrons is also expected to give rise to a variety of electronics properties for applications, if it is possible to form high concentration of theunpaired electrons. It is however, fundamentally difficult to introduce high concentration of unpaired electrons into a crystal in a controlled manner because they result from broken chemical bonds at crystalline imperfections. In this research, as the above-explained attempt, we try to introduce a high concentration of unpaired *sp* electrons in a controlled manner by utilizing the MBE low-temperature growth of Be-doped GaAs (Be:LT-GaAs) layers and derive novel magnetic and magneto-transport properties inherent to these unpaired *sp* electrons.

2. Experimental method

Be-doped LT-GaAs layers were prepared by using a conventional molecular-beam epitaxy (MBE) system at low temperatures. Low temperature growth of GaAs leads to the formation of large numbers of As into the Ga site in the crystal lattice which is known as antisite As, As_{Ga} [2]. These antisite As possess two excess of electrons. To generate high concentration of unpaired electron spin in GaAs, a high concentration of Beryllium (Be) was doped into GaAs during the growth of GaAs, which was performed at relatively low temperatures. Here, Be will accept one of the two excess electrons from antisite As resulting in the formation of As atom with unpaired electron which act as localized spin. We investigate the interactions of localized spins associated with unpaired *sp* electrons with different concentrations by growing several samples at low temperatures, in the range of 200-300ºC. The study of structural and crystallinity of Be:LT-GaAs layers was carried out by using XRD system with a four-crystal monochrometer and high-resolution transmission electron microscopy (HRTEM), prior to magneto and electro-transport measurements. We used super quantum interference device (SQUID) to study the magnetization curve of the unpaired *sp* electrons, in particular *M-H* and *M-T* curves. Electron spin resonance (ESR) was used to detect the existence of localized spins which arise from the unpaired *sp* electrons of antisite As. The hole carrier concentration which was formed by doping Be into antisite As was estimated by Hall effect measurement. Physical properties measurement system (PPMS) was finally used to study the electrical characteristics of the device in the presence of external magnetic field.

2. Results and discussion

Previous study indicates that low temperature grown GaAs layer can achieved up to 20 µm-thick at temperatures around 300ºC [3]. We can expect a further reduce of the growth temperature down to less than 200ºC if we require only few microns of thickness of sample, which enables the formation of even higher localized spin concentrations, up to 4×10^{19} cm^{-3}. Low temperature growth of GaAs leads to the formation of large numbers of As into the Ga site. Higher localized spin concentrations are made possible by doping of high concentration of Be during the growth of GaAs layer by MBE. An XRD pattern (not-shown) of the sample shows a sharp splitting of rocking curve near 35 degrees indicating a clear two distinct epitaxial layers of stoichiometric GaAs substrate and low-temperature grown GaAs layer. A cross section of the sample observed by HRTEM shows a good crystalline structure over the whole layers.

Figure 1 shows the corresponding electron spin resonance (ESR) signal of the sample. The four hyperfine peaks are clearly seen in Be doped sample compared to the non-doped sample. This implies that localized spins from the unpaired electron of antisite As contributed to this peaks. The linewidth ESR spectra changes sensitively by exchange interactions of localized spins [4]. Even weak exchange interactions whose effect on the magnetization can be observed only at

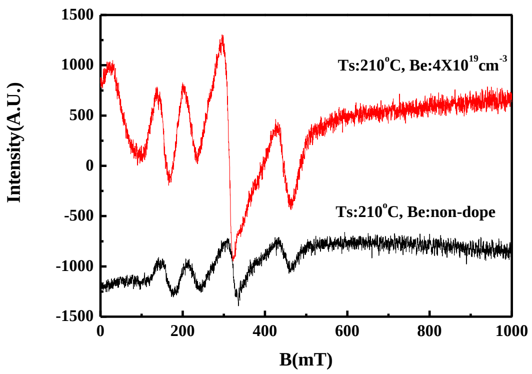

Fig. 1 Change of electron spin resonance (ESR) signal in Be-doped and non-doped GaAs sample.

low temperatures, give rise to a significant effect on linewidth at high temperatures from the measurement of ESR. An earlier study on antisite As defects indicated the significant distribution of an unpaired electron over four nearest-neighbor As atoms and large quadrapole interactions among these four As atoms and the antisite As ion. This is a clear indication showing the existence of localized spins in our sample, originated from the *sp* electrons system.

The interaction between the localized spins was then measured by SQUID to clarify their magnetization behavior by changing the cooling condition and field application. Figure 2 shows the temperature dependence of the magnetization of the localized spins from the sample at low temperatures cooled at three different cooling speeds. The open square, close circle and star symbols indicate slow-cooling, medium cooling and fast-cooling sequence, respectively. As the sample was cooled down from high temperatures to low temperatures, an abrupt drop of magnetization was seen when the sample was fast-cooled, indicating a transition from high magnetization state to low magnetization state occurs at around 3 K. These observations are explained as a result of cooperative transition of spin states of As_{Ga}^{+} ions, which is closely related to the normal-metastable state transition of the EL2 defect in GaAs, and the transformation into metastable state at low temperature occurs without photoexitation process. The changes of magnetization in this samples are expected to affect the conductivity of sample. To demonstrate the application of this phenomenon in a spintronics device, we fabricated a bilayer device consist of high concentration of localized spins from this *sp* electrons and will report the conduction behavior in the presence of magnetic fields.

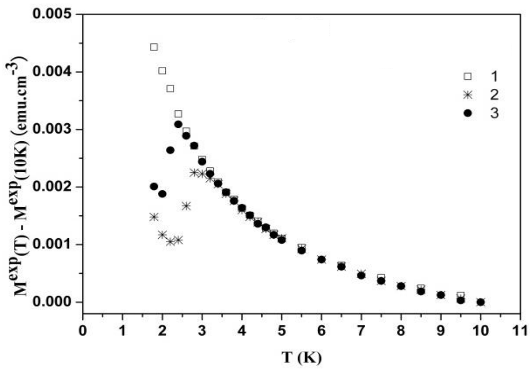

Fig. 2 Magnetic state transition from high spin state to low spin state at different cooling sequences.

3. Conclusions

We have studied magnetic cooperative phenomenon with unpaired sp-electrons system by MBE low-temperature growth. The results from magnetization and transport measurements suggest novel aspects of the transition dynamics resulting from strong coupling between the lattice and localized spin systems in Be-doped LT-GaAs. Even the present system shows magnetic and transport transition phenomenon at low temperature, it will lead to a similar attempt for other semiconductors, in particular for Si.

Acknowledgements

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