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Spin Dependent Phenomena in Magnetic and Non-Magnetic III-V's

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1. Introduction

Modern information technology is based on charge and spin of electrons. Semiconductor devices utilize charge of electrons in semiconductors, whereas magnetic storage takes advantage of spin of electrons in magnetic materials. It is then quite natural to ask oneself whether one can use both charge and spin of electrons at the same time, especially in semiconductors, to enhance the device performance and to create new functionality that enriches further the already flourishing semiconductor electronics.

Semiconductors used in electronics such as Si and GaAs are non-magnetic; that is, it contains no magnetic ions. This makes properties of Si and GaAs relatively insensitive to the spin orientation of carriers; for example, to create 1 meV of energy difference in the two possible directions of electron spin, magnetic fields of the order of 10 T is required. This insensitivity is the reason why most of the spin-dependent phenomena could be virtually ignored in semiconductor device operations.

There are several ways to enhance the magnitude of spin sensitivity. When magnetic ions are introduced in non-magnetic semiconductors, exchange interaction between band electrons and electrons localized at the magnetic ions modifies the properties of semiconductors and the spin-dependent phenomena are magnified. In non-magnetic semiconductors, one can create spin polarization by the use of circularly polarized light, which may alter the optical response of semiconductors. Or when electrons are confined in a smaller volume, the exchange interaction among them becomes increasingly important even without magnetic ions. Since semiconductor electronics is currently reducing its working dimension in an exponential way, sooner or later we will need to deal with the exchange interaction in small structures, where the interaction becomes spin dependent.

The present paper reviews the recent advances in the study of spin-dependent phenomena in III-V compound, the semiconducting compounds widely used for high-speed transistors and lasers. The introduction of magnetic ion Mn in III-V's, especially in GaAs, demonstrated that enhanced spin-carrier interaction could lead to ferromagnetism and spontaneous spin splitting of semiconductor bands when the ferromagnetic order sets in. The emphasis of this paper is placed on the recent results on (Ga,Mn)As. The spin-dependent phenomena in non-magnetic III-V's are also reviewed from the electronics point of view.

2. Spin-Dependent Properties of Magnetic III-V's : Ferromagnetic (Ga,Mn)As

2.1 Preparation

Because of the low solubility of magnetic ions in GaAs, the introduction of high concentration of magnetic ions into GaAs to enhance spin-related phenomena has long been very difficult. Recently, the low solubility of Mn in GaAs was overcome by low temperature molecular beam epitaxial growth and GaAs was shown to become not only magnetic but ferromagnetic [1]. The surface reconstruction of (Ga,Mn)As grown on (001) GaAs substrates was clear streaky (1x2) during and after growth at 250 °C, showing the high crystal quality of the layers. Lattice constant of (Ga,Mn)As is found to be a linear function of Mn composition following Vegard's law, which suggests that Mn is incorporated substitutionally in the GaAs host lattice. The maximum Mn concentration so far obtained is 7%, above which Mn segregation and MnAs formation takes place even at low growth temperatures.

2.2 Magnetic properties and spin-dependent transport

III-V based ferromagnetic (Ga,Mn)As offers an opportunity to explore various aspects of carrier transport in the presence of cooperative phenomena, since they are conducting, can be doped to p- or n-type, and are compatible with GaAs/AlAs based heterostructures.

Magnetization measurements showed that (Ga,Mn)As is ferromagnetic with Curie temperature T_C as high as 110 K (5% Mn). The easy axis for magnetization was in-plane. All nominally undoped uniform alloys (Mn composition up to 7 %) showed p-type conduction with hole concentration in the range of high 10^{18} - mid 10^{20} cm^{-3} due to the acceptor nature of Mn. Magnetotransport measurements of (Ga,Mn)As films grown on (001) GaAs substrates revealed that the temperature dependence of resistivity ρ is characterized by critical scattering (scattering by spin fluctuation). From the fit of magnetic field dependence of ρ above T_C to the spin disorder scattering formula, the *p-d* exchange $N_0\beta$ was determined to be about 3 eV. This interaction between the localized magnetic moments and conduction holes, which may have been enhanced by the presence of electron-electron interaction, is large enough to explain the ferromagnetic interaction and the high T_C (in view of the low Mn and hole concentrations) observed in (Ga,Mn)As by the Ruderman-Kittel-Kasuya-Yosida interaction [2].

2.3 Heterostructures based on (Ga,Mn)As

Transport properties of AlAs/GaAs/AlAs double barrier resonant tunneling diode (RTD) structures with ferromagnetic p-type (Ga,Mn)As on one side and p-type GaAs on the other have been studied. When holes are injected from the (Ga,Mn)As side, a spontaneous resonant peak splitting in the conductance-voltage characteristic has been observed below T_C of (Ga,Mn)As without magnetic field. The magnitude of the splitting can be described by the temperature dependence of saturation magnetization calculated from a Brillouin function, showing the origin of peak splitting being the spin splitting in the valence band of the emitter material of RTD, ferromagnetic (Ga,Mn)As [3]. The splitting is at least as large as 40 meV. Magnetic field in excess of 400 T would have been required to produce similar splitting if there were no exchange interaction. This result also indicates the possibility of injection of spin-polarized carriers in non-magnetic structures using the combination of ferromagnetic semiconductor and an RTD structure.

All-semiconductor based ferromagnet/nonmagnet/ ferromagnet trilayer structures using (Ga,Mn)As as a ferromagnetic layer and GaAs or (Al,Ga)As as a nonmagnetic layer were prepared and their magnetotransport properties were also investigated. The results show that the interaction between the two (Ga,Mn)As layers decreases as the GaAs thickness increases or Al content of the (Al,Ga)As spacer increases. This indicates the critical role of carriers present in the nonmagnetic layer in mediating the coupling between the two ferromagnetic layers in the present all-semiconductor system. This first observation of magnetic coupling in all-semiconductor ferromagnetic/nonmagnetic layered structures shows the potential of the present material system for exploring new physics as well as for developing new functionality for future electronics [4].

2.4 Other magnetic III-V's

The first III-V based magnetic semiconductor (In,Mn)As was synthesized by low temperature molecular beam epitaxy in 1989 [5], in which partial ferromagnetic order was found [6]. (In,Mn)As/(Al,Ga)Sb heterostructures were recently found to exhibit photo-induced ferromagnetism; photo-generated holes separated from electrons by the internal electric field and accumulated in the (In,Mn)As layer triggered ferromagnetism of the (In,Mn)As layer, which is believed to be hole induced like (Ga,Mn)As [7]. Although demonstrated at low temperature, it will open up a unique possibility of controlling magnetism by controlling the density of carriers.

3. Spin-Dependent Phenomena in Non-Magnetic III-V's

Although there have been numerous studies on the physics of spin-dependent phenomena in non-magnetic III-V's, the effect has rarely been approached from the application point of view. There are two areas of studies that are significant in this respect.

One is the utilization of spin-state in III-V's. This can further be subdivided into two categories. One is the use of ultrafast spin-relaxation process in GaAs quantum wells (QW) demonstrated by Tackeuchi et al. [8]. One can create electron spin polarization in QW by circularly polarized light, which modifies the absorption of subsequent left and right circularly polarized light while the polarization lasts. This effect can be used for a sub 10 ps optical gate switch at room temperature. The other is the use of coherent nature of spin precession. It has been demonstrated that the spin coherence time can be relatively long (> 100 ns) at low temperature in lightly doped GaAs [9]. If this is long enough, one may be able to use spin coherence in III-V's for quantum computing. Detailed studies are required to understand and to control the spin-relaxation mechanisms that determine the ultrafast (<10 ps) spin-relaxation time in QW's and the relatively long (> 100 ns) spin coherence time in lightly doped GaAs. In an effort to elucidate the mechanisms, we have studied the relationship between the carrier scattering time and the spin-relaxation time in GaAs QW at room temperature [10].

The other significant work is the observation of shell filling in man-made atoms of GaAs nano-structures by Tarucha et al. [11], which points our what would happen when the semiconductor structure becomes small enough.

4. Conclusion

Recent developments in the study of spin-related phenomena in magnetic and non-magnetic III-V semiconductors were reviewed. The rapid developments encourage us to believe that the spin-dependent phenomena can be used in future to enhance the device performance and to add new functionality to wide range of semiconductor electronics.

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