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A magnetic quantum dot in a diluted magnetic semiconductor/semiconductor heterostructure ☆

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ABSTRACT

A circular quantum dot consisting of a diluted magnetic semiconductor and a nonmagnetic semiconductor in the presence of a constant magnetic field is theoretically investigated. Electron eigenenergies and eigenstates are calculated using effective mass approximation. We show how the spin up and spin down eigenenergies vary with the effective g-factor. Spin-dependent distribution of electron wavefunctions is found. The approximation of the eigenenergies is also discussed.

1. Introduction

A diluted magnetic semiconductor (DMS) [1–3] is a compound semiconductor formed by doping of a nonmagnetic semiconductor (NMS) by magnetic ions. Magnetic properties in a DMS caused by the impurities have attracted much attention. In a paramagnetic DMS, an external magnetic field gives rise to not only the normal Zeeman splitting but also the strong exchange interaction between band electrons in a DMS and those associated with magnetic ions. As a result, the energy splitting is extremely enhanced. This phenomenon can be interpreted by introducing the effective g-factor (g_{eff}) which is much larger than the g-factor of band electrons. Experimental studies show the value of g_{eff} can be tuned to several hundreds, depending upon magnetic concentration, temperature, and host semiconductors [4,5].

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According to the giant Zeeman effect, a DMS has become one of the most potential materials for spintronic application which aims to manipulate spin and charge of carriers [6,7]. One example of the application is spin polarized bound states which are created in a DMS layer in the presence of non-homogeneous magnetic fields associated with permalloy disks, Abrikosov vortices, and Josephson vortices [8–10]. When g_{eff} is sufficiently large, the Zeeman energy will become a major confinement potential, while the potential due to a magnetic vector potential can be neglected. The energy spectrum of the Zeeman-bound states is therefore found to be influenced by magnetic field profiles.

Another possibility is to use a DMS as a tunnel junction. It was first investigated by Egues [11] who focused on the ZnSe/ZnMnSe/ZnSe heterostructure. Based on the concept that spin up and spin down electrons feel different potentials in the region of a DMS, a spin-polarized current can be achieved after injected electrons tunnel through a DMS. Using the different method, Chang and Peeters [12] revisited the problem to support the work of Egues. They additionally investigated the effect of the DMS thickness on spin-dependent conductivity. In the other studies of the heterostructure [13–15], the effects of the Mn concentration, conduction band offset, and applied electric field are included to improve the spin polarization. The results from related systems consisting of DMSs also show the possibility of spin-polarized tunnelling [16–18].

Moreover, DMSs are applied to quantum dots. They have been studied for different geometries: a cylinder, a sphere, and a cuboid [19–24]. Interestingly, Triki et al. [25] proposed the quantum dot heterostructure which is formed by CdMnSe (CdSe) in the shape of a truncated cone surrounded by ZnSe (ZnMnSe) and numerically studied the variation of electron energies as a function of a magnetic field. In the heterostructure, the potential due to the band offset, which is discussed intensively, plays a major role in electron confinement while the giant Zeeman potential only leads to energy splitting of spin up and spin down states.

In this work, we analytically investigate the DMS/NMS quantum dot formed by a disk-shaped DMS surrounded by a NMS as depicted in Fig. 1, focusing on the effect of the giant Zeeman potential. To see the effect clearly, we study the quantum dot where a host semiconductor of a DMS is the same material as a surrounding NMS. In this heterostructure, only the confinement due to the giant Zeeman potential exists while the band offset at the interface can be ignored. The spin-dependent energy spectrum and distribution of electron states are discussed and classified. Without the band offset, we find spin up and spin down states exhibit completely different spatial distribution. These behaviors of spin states may be useful for the application of spin-based memories or future spintronic devices [26–28].

2. Theoretical formulations

Within the mean field approximation, the potential energy of a conduction band electron travelling in a DMS subjected to a magnetic field $\vec{B} = B\hat{z}$ is given by

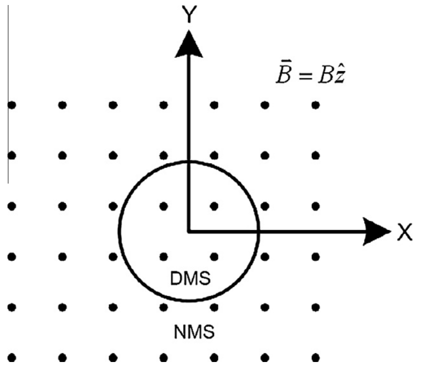

Fig. 1. The hybrid system of a circular DMS surrounded by a NMS in a uniform magnetic field $\vec{B} = B\hat{z}$ represented by the symbol •.