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# High and electric field tunable Curie temperature in diluted magnetic semiconductor nanowires and nanoslabs

Xiu-Wen Zhang<sup>a)</sup>

*Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China and School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore*

Wei-Jun Fan

*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore*

Yu-Hong Zheng, Shu-Shen Li, and Jian-Bai Xia

*Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China*

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The Curie temperature of diluted magnetic semiconductor (DMS) nanowires and nanoslabs is investigated using the mean-field model. The Curie temperature in DMS nanowires can be much larger than that in corresponding bulk material due to the density of states of one-dimensional quantum wires, and when only one conduction subband is filled, the Curie temperature is inversely proportional to the carrier density. The  $T_C$  in DMS nanoslabs is dependent on the carrier density through the number of the occupied subbands. A transverse electric field can change the DMS nanowires from the paramagnet to ferromagnet, or vice versa. © 2007 American Institute of Physics. [DOI: 10.1063/1.2750539]

Semiconductor and ferromagnetic metals play complementary roles in current information processing and storage technologies. The discovery of ferromagnetism in diluted magnetic semiconductors<sup>1</sup> (DMSs) paves the way for it to play the two roles together. To make the devices work at room temperature, people are searching for high Curie temperature ( $T_C$ ) DMSs.  $T_C$  in excess of 300 K has been realized in various DMS systems.<sup>2,3</sup> These DMS systems have potential application in spintronics. The efficient spin injection from ferromagnetic DMSs into normal semiconductors was demonstrated.<sup>4</sup> People have been searching electrically tunable ferromagnetic DMSs for decades. The origin of ferromagnetism in DMSs has been investigated using a mean-field model,<sup>5-8</sup> which was first proposed by Zener<sup>5</sup> and then extended by Dietl *et al.*<sup>6,7</sup>

The investigations of quantum confinement of carriers in spatially modulated semiconductor structures have been a field of intense activity over the past decades. High-quality and ultrathin nanowires were synthesized,<sup>9</sup> and the method to dope Mn ions into these nanowires was achieved.<sup>10,11</sup> DMS nanoslabs were widely synthesized.<sup>12,13</sup> The properties of DMS nanowires and nanoslabs were investigated extensively,<sup>10-14</sup> the room temperature ferromagnetism was found in DMS nanowires,<sup>10,11</sup> and the effects of quantum confinement on  $T_C$  were discussed.<sup>13</sup> The Curie temperature in DMS nanowires<sup>14</sup> can be much larger than the corresponding bulk  $T_C$ .

In this letter, we investigate the Curie temperature of Mn-doped DMS nanowires and nanoslabs. The influence of quantum confinement of carriers on  $T_C$  will be discussed thoroughly. We assume that the nanowire has the cylindrical symmetry, the longitudinal axis is along the  $z$  direction, and the electrons are confined laterally in an infinitely high po-

tential barrier. The electron states in nanowires and nanoslabs were calculated in Ref. 15. In the mean field model, the carriers mediate a long-range ferromagnetic exchange interaction between magnetic ions, the Curie temperature of bulk DMSs can be calculated by<sup>7</sup>

$$T_C = \frac{2}{3} x_{\text{eff}} N_0 S(S+1) (g\mu_B)^2 \frac{F_c[0] - F_c[M]}{k_B M^2} - T_{\text{AF}}, \quad (1)$$

where  $x_{\text{eff}}$  is the effective concentration of Mn ions,  $N_0$  is the number of cations per unit volume,  $S=5/2$  and  $g=2$  are the spin and  $g$  factor of a Mn ion,  $M$  is the magnetization of the localized spins of Mn ions, and  $T_{\text{AF}}$  represents the influence of antiferromagnetic superexchange. From now on, we take  $T_{\text{AF}}=0$  because  $T_{\text{AF}}$  is small.  $F_c$  is the Helmholtz free energy, and in the degenerate case  $F_c$  has the simple form,

$$F_c(n_e, M) = \int_0^{E_F} E(M) N(E) dE, \quad (2)$$

where  $n_e$  is the electron density,  $N(E)$  is the density of states,  $E_F$  is the Fermi level.

For DMS nanowires, when only one conduction subband is filled, we deduce  $F_c[0] - F_c[M] = m_e^* \alpha^2 M^2 / [\pi^2 D^2 \hbar^2 (g\mu_B)^2 k_{F_z}]$ ,  $\alpha$  is the  $s$ - $d$  exchange constant between the electrons and Mn ions. Thus the Curie temperature is

$$T_C = \frac{2}{3} x_{\text{eff}} N_0 S(S+1) \frac{m_e^* \alpha^2}{k_B \pi^2 D^2 \hbar^2 k_{F_z}} \frac{1}{3} = \frac{16}{3} x_{\text{eff}} N_0 S(S+1) \frac{m_e^* \alpha^2}{k_B \pi^4 D^4 \hbar^2 n_e}, \quad (3)$$

where  $D=2R$  is the diameter of the nanowire and  $k_{F_z}=(1/8)\pi^2 D^2 n_e$  is the Fermi wave vector. We note that  $T_C$  is inversely proportional to  $D^4$ , so  $T_C$  will increase dramatically as  $D$  decreases.  $T_C$  is also inversely proportional to  $n_e$ .

<sup>a)</sup>Electronic mail: zhwxw99@semi.ac.cn

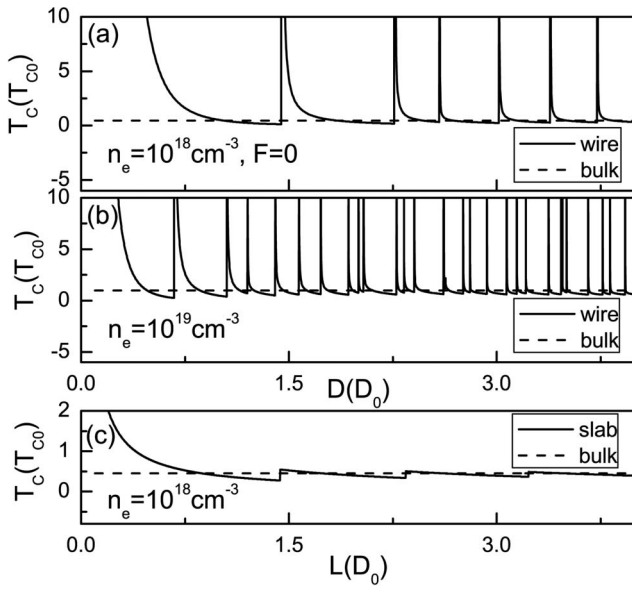


FIG. 1. Curie temperatures of DMS nanostructures in the absence of electric field as functions of the dimensions. (a) Wire,  $n_e = 10^{18} \text{ cm}^{-3}$ , as a function of  $D$ . (b) Wire,  $n_e = 10^{19} \text{ cm}^{-3}$ . (c) Slab,  $n_e = 10^{18} \text{ cm}^{-3}$ , as a function of  $L$ . Dashed lines are the bulk cases.

When  $n$  conduction subbands are filled, the Curie temperature is

$$T_C = \frac{2}{3} x_{\text{eff}} N_0 S(S+1) \frac{m_e^* \alpha^2}{k_B \pi^2 D^2 \hbar^2} \sum_n \frac{1}{k_{Fzn}} = \frac{1}{12} x_{\text{eff}} N_0 S(S+1) \frac{\alpha^2}{k_B} N(E_F). \quad (4)$$

We note that  $T_C$  is proportional to the density of states at the Fermi level, because the carriers in these states mediate the ferromagnetism.<sup>7</sup>

It is easy to deduce the Curie temperature of the two-dimensional semiconductor slabs (quantum wells or thin films) with enough high barrier,

$$T_C = \frac{1}{12} x_{\text{eff}} N_0 S(S+1) \frac{nm_e^* \alpha^2}{k_B \pi L \hbar^2}, \quad (5)$$

where  $L$  is the thickness of slabs, and  $n$  is the number of the filled subbands. From Eq. (5) we note that in the one filled subband case ( $n=1$ ), the Curie temperature of the slab is independent of the electron density and inversely proportional to the thickness of the slab  $L$ .

Besides, the Curie temperature of DMS bulk material is deduced as

$$T_C = \frac{3^{1/3}}{12} x_{\text{eff}} N_0 S(S+1) \frac{m_e^* \alpha^2}{k_B \pi^{4/3} \hbar^2 n_e^{1/3}}. \quad (6)$$

The Curie temperatures can be calculated by Eqs. (4)–(6). Figures 1(a) and 1(b) show the Curie temperatures of DMS nanowires. The dashed lines are those of the bulk materials. The units of  $D$  and  $T_C$  are  $D_0 = \sqrt{\hbar^2 / (2m_e^* E_0)}$  and  $T_{C0} = (2/3) x_{\text{eff}} N_0 S(S+1) m_e^* \alpha^2 / (k_B \pi^2 D_0^2 k_0 \hbar^2)$ , respectively, where  $E_0 = 1 \text{ meV}$  and  $k_0 = 1/D_0$ . Comparing the solid lines and dashed lines, we find that the Curie temperature of DMS nanowires is quite larger than that of the corresponding bulk DMSs in many cases, due to the density of states of one-dimensional quantum wires. The first decreasing ranges of

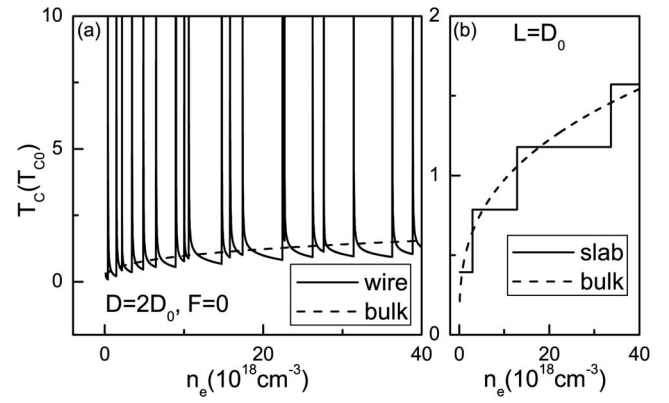


FIG. 2. Curie temperatures of DMS nanostructures at  $F=0$  as functions of  $n_e$ . (a) Wire,  $D=2D_0$ . (b) Slab,  $L=D_0$ .

the solid lines correspond to the one filled subband cases [Eq. (3)]. We find that as  $D$  increases, the Curie temperature decreases rapidly following the  $D^{-4}$  law. When the  $D$  increases for the fixed electron density the Fermi level crosses sequentially the bottoms of subbands where the density of states is infinite,  $T_C$  jumps and then decreases again. Comparing Figs. 1(a) and 1(b), as the carrier density increases, the bulk  $T_C$  increases, and the wire  $T_C$  decreases in the small  $D$  range where only one subband is filled. In the large  $D$  range, the case is complicated because there are more jumps in Fig. 1(b). We point out that in Fig. 1(a), the Curie temperature may be very large for a relatively low carrier density. There are doping bottlenecks<sup>16</sup> in some bulk semiconductors in which high carrier density is hard to achieve. Therefore, the DMS nanowires can overcome the doping bottlenecks which restricts the application of some bulk DMSs. Figure 1(c) shows the Curie temperature of DMS nanoslabs. We note that as  $L$  increases in small  $L$  range,  $T_C$  decreases following the  $L^{-1}$  law, as  $L$  increases further, the number of the occupied subbands increases, so the  $T_C$  increases stepwise and then decreases again.

Figure 2(a) shows that as  $n_e$  increases the wire  $T_C$  jumps at some carrier densities  $n_{ei}$  then decreases as  $(n_e - n_{ei})^{-1}$ ; while the bulk  $T_C$  increases with increasing  $n_e$ , as a function of  $n_e^{1/3}$ . Figure 2(b) shows that the slab  $T_C$  has some plateaus corresponding to different numbers of the occupied subbands  $n$  [see Eq. (5)]. Thus the slab  $T_C$  is dependent on  $n_e$  only through  $n$ .

Figures 3(a) and 3(b) show the electron levels of (Zn,Mn)O nanowires. The dashed lines are the Fermi levels. For ZnO, we use  $m_e^* = 0.28m_0$  and  $\alpha N_0 = 0.19 \text{ eV}$ .<sup>12</sup> The electron states are labeled with  $S$ ,  $P$ , and  $D$ , which correspond to the Bessel functions with  $L=0$ , 1, and 2, respectively. The electric field makes the fourfold degenerate  $P$  and  $D$  levels split into two double degenerate levels, due to the breaking of the cylindrical symmetry of the nanowires. It is noticed that the energy differences between the levels are changed largely by the electric field, especially when the diameter is large. This change of energy differences will affect the Curie temperature dramatically. Figures 3(c) and 3(d) show the Curie temperatures as functions of the diameter. The peaks correspond to the jump to the  $D$  subbands. We note that there are two jumps in the  $F=10 \text{ mV/nm}$  case whose diameter positions are both quite different from that of the jump in the  $F=0$  case. The reason is that as the levels split and the energy differences between levels varies, the electron filling process

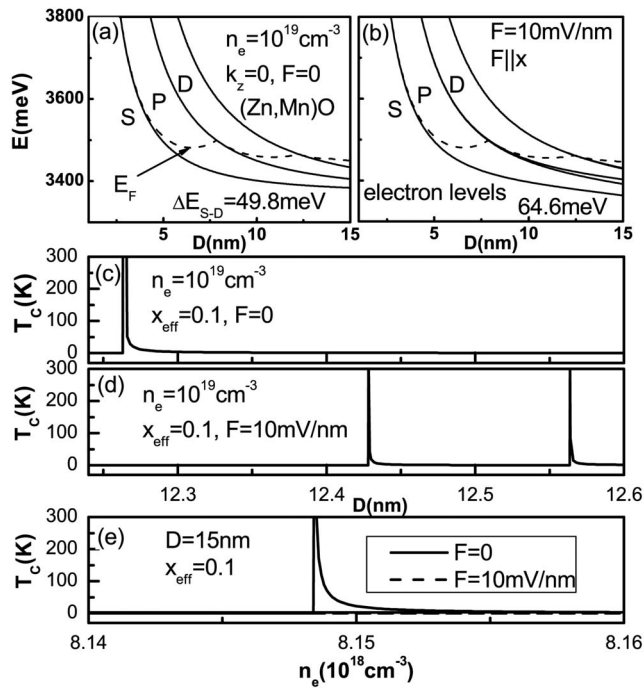


FIG. 3. (a) Electron levels of (Zn,Mn)O nanowires with  $n_e = 10^{19} \text{ cm}^{-3}$  at  $k_z = 0$  and  $F = 0$  as functions of  $D$ . (b) Similar to (a) but  $F = 10 \text{ mV/nm}$  ( $F \parallel x$ ). (c) Curie temperature of (Zn,Mn)O nanowires with  $n_e = 10^{19} \text{ cm}^{-3}$  and  $x_{\text{eff}} = 0.1$  at  $F = 0$  as a function of  $D$ . (d) Similar to (c) but  $F = 10 \text{ mV/nm}$ . (e) Curie temperatures of (Zn,Mn)O nanowires with  $D = 15 \text{ nm}$  and  $x_{\text{eff}} = 0.1$  as functions of  $n_e$ .

is changed. We see from Fig. 3(c)–3(e) that the electric field can change the DMS nanowires from the ferromagnet to paramagnet, or vice versa. If the ferromagnetic DMS nanowires are used to inject the spin polarized current into the normal semiconductors,<sup>4</sup> we can use a transverse electric field to turn on or turn off the spin injection.

In summary, the Curie temperature of DMS nanowires and nanoslabs was studied using the mean-field model. The quantum confinement of carriers affects the Curie temperature  $T_C$  greatly. The  $T_C$  in DMS nanowires can be much larger than that in corresponding bulk material due to the density of states of one-dimensional quantum wires. When only one conduction subband is filled,  $T_C$  is inversely proportional to carrier density and  $D^4$ . When many subbands are

filled,  $T_C$  jumps as the Fermi level crosses the bottom of subbands, and then decreases. The  $T_C$  in DMS nanoslabs is dependent on the electron density through the number of the filled subbands  $n$ , and inversely proportional to the thickness of the slab  $L$  when only one subband is filled. A transverse electric field can be used to modulate the DMS nanowires between the ferromagnetic and paramagnetic states, so turning on or turning off the spin injection into the normal semiconductors.

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