N 型強磁性半導体(In,Fe)As 量子井戸における波動関数制御による電気的な磁性変調

Electrical modulation of ferromagnetism via controlling the wavefunctions in n-type ferromagnetic semiconductor (In,Fe)As quantum wells

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Among many ferromagnetic semiconductors (FMSs), (In,Fe)As is promising because it is n-type with electron-induced ferromagnetism [1,2,3]. Electron carriers in (In,Fe)As are found to reside in the conduction band, thus having small effective mass, relatively high mobility, and long coherence length. In quantum wells (QWs) containing an (In,Fe)As thin layer, the magnetic properties can be tuned by controlling the two-dimensional wavefunctions using a gate voltage V_G [4]. Here, we have experimentally demonstrated for the first time this concept, which enabled us to effectively control the Curie temperature (T_C) of a (In,Fe)As thin film without the need of accumulating or depleting carriers. This will greatly reduce the power consumption and operation time for manipulating the magnetic properties.

Two trilayer QW structures (A and B) were prepared: Sample A consists of InAs (2nm)/($In_{0.94}$,$Fe_{0.06}$)As (8nm)/InAs (5nm) on AlSb (50nm), while sample B consists of InAs (2nm)/($In_{0.94}$,$Fe_{0.06}$)As (5nm)/InAs (2nm)/InAs:Si (5nm, Si 5×10^{18} cm^{-3}) on AlSb (300nm). The samples were then etched into a 50×200 μm^2 Hall bars; Au/Cr side-gate electrodes were deposited; then the channels were covered with electrolyte to form the field-effect-transistors. The transport and magnetic properties of the trilayer QWs were characterized mainly by Hall measurements. As illustrated in Fig. 1(a), due to the different designs, one can use a positive gate voltage V_G to reduce the overlap of the carrier wavefunctions and the (In,Fe)As layer in Device A, while enlarge the overlap in Device B. As a result, without largely changing the sheet electron densities (n_{sheet}) of the QWs, T_C of the (In,Fe)As layers were largely modified: In Device A, T_C decreased from 24 K (V_G = 0 V) to 17 K (V_G = 6 V) and 14 K (V_G = –3 V), while in Device B, T_C increased from 27 K (V_G = 0 V) to 35 K (V_G = 2 V) and 30 K (V_G = 4 V). Calculations using the mean-field Zener model for FMS QWs were performed, which show good agreement with the experimental results (Fig. 1(b)). The different behavior of T_C in the two QWs have demonstrated the high degree of freedom of the new concept, which allows one to tune the T_C - V_G relation by the QW structure. The reversible control of the ferromagnetism of n-type FMS (In,Fe)As by a gate voltage proves its intrinsic electron-induced ferromagnetism, as well as opens up new possibilities of device applications.

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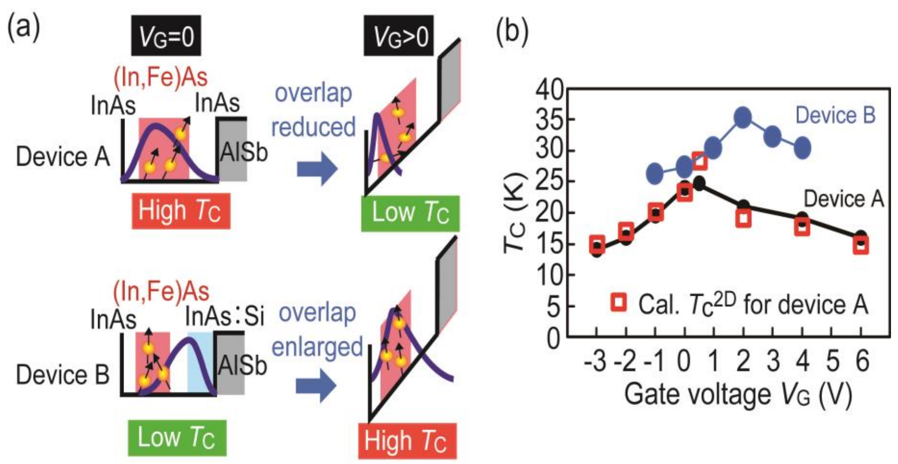

Fig. 1 (a) Schematic electronic structure of the trilayer InAs/($In_{0.94}$,$Fe_{0.06}$)As/InAs QWs in devices A and device B at V_G = 0 (left panels) and V_G>0 (right panels). (b) Experimental T_C of device A (black circles) and device B (blue circles) and calculated T_C for device A (red squares) as functions of V_G.