DILUTED MAGNETIC III–V SEMICONDUCTORS

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During recent years diluted magnetic semiconductors based on III–V compounds have been of considerable interest. In this respect we review the basic properties of these materials, which are nearly exclusively Mn-based systems, such as GaMnAs, InMnAs, GaMnSb, and GaN:Mn. We discuss the nature of Mn impurity. Different Mn centers are considered and experimental pieces of evidence suggesting the dominating role of Mn (d^5) configuration are given. Then we analyze s, p–d exchange, together with resulting magnetooptical properties (in particular absorption edge slitting for heavily p-type GaMnAs). The coupling between Mn ions (d–d exchange) and ferromagnetic ordering observed in InMnAs and GaMnAs is the next subject. Some mechanisms responsible for this ordering are presented. Finally we discuss transport properties and some selected problems of quantum structures based on III–V diluted magnetic semiconductors.

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1. Introduction

During last two decades a broad class of materials called diluted magnetic semiconductors (DMS) has been intensively studied [1–3]. These materials are based on classical semiconductors, for which a controlled fraction of nonmagnetic cations has been substituted by magnetic ions. Most of the research done so far has been devoted to DMS based on II–VI compounds with Mn, Fe, and Co (e.g. $Cd_{1-x}Mn_xTe$, $Zn_{1-x}Fe_xSe$), as well as IV–VI crystals with Mn or Eu (e.g. $Pb_{1-x}Mn_xTe$, $Pb_{1-x}Eu_xTe$). Typical properties of DMS can be summarized as follows: Semiconductor properties are strongly influenced by s, p–d exchange interaction, which leads to large bands splittings. This way transport and optical properties are very sensitive to magnetic field, to mention giant magnetooptical effects [1]. On the other hand, magnetic properties of DMS are typical of ensemble of localized magnetic moments associated with transition metal or rare earth ions. There is a pronounced coupling between magnetic moments, which typically (e.g. Mn-based II–VI DMS) is antiferromagnetic (AFM) superexchange [4]. This d–d exchange may produce a spinglass phase in a certain temperature and composition range [1–3], as well as a truly long ranged AFM order [5, 6]. For the systems

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with high free holes concentration carrier induced ferromagnetic (FM) coupling occurs [7, 8]. This coupling may override AFM superexchange and yield FM ordering of magnetic moments system. Regarding magnetic and optical properties of II–VI DMS it is worthwhile to stress the role of epilayers and quantum structures grown by MBE techniques [9].

The III–V DMS are much more attractive than II–VI materials, as they are probably much more usable for device fabrication. For a long time these materials were unavailable, since it was not possible to obtain III–V crystals with a reasonable concentration of magnetic ions. Only the application of MBE methods resulted in crystals with few molar percent of Mn [10–22]. Both quasi 3D epilayers, as well as quantum structures were obtained [18]. A very attractive feature of Mn-based III–V DMS is hole induced FM [20, 17, 19, 23].

In this respect we review the basic properties of III–V DMS.

2. Materials

The equilibrium growth of III–V compounds with magnetic ions is limited by rather a low solubility of Mn or other magnetic elements, so only very dilute ($x < 0.001$) crystals were obtained. Attempts to grow materials with sizable Mn content resulted in increasing volume of precipitations of the other phases (e.g. such as Mn_yAs_z). This problem has been overcome by the use of low temperature (below 300°C) MBE techniques (LT-MBE) [17, 19]. The details of growth were described elsewhere [11, 15, 19, 24, 25]. Since the times of the pioneering work for InMnAs [10, 11], the other systems such as GaMnAs [15, 19], GaFeAs [26], and GaMnSb [27] were also obtained. So far, the most popular III–V DMS are InMnAs and GaMnAs.

The local structure around Mn ions was investigated by extended X-ray absorption fine structure (EXAFS). For both InMnAs and GaMnAs it was shown that in general Mn substitutes cation sublattice (In or Ga) [28]. It is worthwhile to mention that annealing of LT GaMnAs leads to segregation: Mn concentrates in MnAs precipitates leaving apart nearly pure GaAs [29].

Most of III–V DMS reveal a reasonably good conductance, which is driven by either holes or electrons [12, 30, 31]. A very high hole concentration (up to 10^{20} cm^{-3}) is characteristic of GaMnAs [24, 31]. Depending on the Mn concentration and growth conditions a typical semiconductor, as well as metallic behavior, may be observed.

3. The nature of Mn impurity

Manganese impurity in III–V compounds has been studied for a long time [32–48]. The present understanding of the situation can be summarized as follows: There are essentially three types of Mn centers in III–V compounds. The first one is formed by substitutional manganese Mn_{Ga}^{3+}, which is in d^4 configuration (we denote this center by $A^0(d^4)$). $A^0(d^4)$ was observed in GaP:Mn, in EPR experiment [48]. On the other hand, for GaAs $A^0(d^4)$ centers were not reported.

The second type of Mn center appears when the center $A^0(d^4)$ traps an electron and binds it tightly at the d-shell. Such center can be regarded as a d^5

configuration, with $S = 5/2$. It is negatively charged and can therefore attract and (weakly) bind a hole, forming a $(d^5 + h)$ complex of neutral acceptor $A^0(d^5 + h)$ [35]. Due to exchange interaction between the d-shell ($S = 5/2$) and the bound hole ($j = 3/2$), the ground state of $A^0(d^5 + h)$ may have a total angular momentum $J = 4$ (for FM interaction between the hole and the ion) or $J = 1$ (for AFM interaction). The EPR spectra of some GaAs:Mn [35] were interpreted assuming $A^0(d^5 + h)$ center with a triplet ground state ($J = 1$). This conclusion was corroborated by infrared spectroscopy data, which revealed an acceptor level at about 0.113 eV above the top of the valence band [32]. The spectrum of this acceptor was thoroughly studied under the presence of uniaxial stress and magnetic field [44, 45, 49]. The results give the strong support for the $A^0(d^5 + h)$ impurity center [49]. Also the magnetic data of GaAs:Mn could be successfully described taking into account $A^0(d^5 + h)$ centers [40, 50]. The lack of $A^0(d^4)$ centers has been recently explained by configuration cluster-model calculations, which show that for GaAs the ground state of neutral acceptor is dominated by $(d^5 + h)$ configuration [51].

The third type of Mn centers arises from ionization of neutral acceptor $A^0(d^5 + h) \rightarrow A^-(d^5) + h$, where the ionized acceptor $A^-(d^5)$ is in d^5 configuration. Such center is equivalent to Mn^{2+} ion in II–VI compounds. Its ground state is a spin sextet $^6A_1$ ($S = 5/2, L = 0$). The EPR spectra characteristic of $A^-(d^5)$ were observed for GaP as well as for GaAs[†] [33, 34]. It seems therefore rather well established that for bulk GaAs manganese impurity occurs either as a neutral $(d^5 + h)$ or ionized (d^5) acceptor center.

The situation for the GaMnAs epilayers is different: only a single EPR line was observed with the g-factor around 2.00 [52]. This line was ascribed to the A^- center. It was suggested that the observed line results from the broadening of the 6-line structure with increasing Mn concentration, in analogy with II–VI Mn-based DMS [53, 54].

On the other hand, no A^0 was observed in any of the investigated epilayers. The likely reason for such a situation is the high free hole concentration in the epilayers [24, 31], which screen the Coulomb potential of $A^-(d^5)$ center and reduce the hole binding energy. This way holes easily ionize and only A^- centers are left.

Essentially a similar situation occurs in InMnAs: a single line with g^* around 2 was visible, with no traces of other absorption, which could be ascribed to A^0 complex [55].

The results of EPR investigations of GaMnAs and InMnAs epilayers can be thus summarized as follows: it is very likely that in the epilayers the dominant Mn impurity is ionized acceptor $A^-(d^5)$ with spin $S = 5/2$ and orbital momentum $L = 0$.

4. s, p–d exchange interaction

Exchange interaction between s- and p-type band electrons and d electrons of Mn ions in III–V DMS can most probably be described in a similar way as it

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[†]The hyperfine splitting in principle should be also observed for $A^0(d^5 + h)$ and $A^0(d^4)$, but the EPR lines were too broad to resolve the hyperfine structure.

was done for Mn-based II–VI DMS, i.e. by a simple isotropic Heisenberg Hamiltonian [56]: $\mathcal{H} \sim -JNx\langle S \rangle \cdot s$, where mean field approximation (MFA) and virtual crystal approximation have been used. Since $Nx\langle S \rangle$ is proportional to macroscopic magnetization of the crystal, the exchange effects should be parametrized by magnetization (following magnetization magnetic field and temperature dependence). Such situation was encountered in II–VI DMS and is considered as a sort of fingerprint of $s, p-d$ exchange [57].

The $s, p-d$ exchange results in strong band splittings, typically of the order of tens of meV. The exchange for the conduction band ($s-d$ exchange, characterized by $J_{s-d} \sim \alpha$) is always ferromagnetic ($\alpha > 0$), since this is a one-center potential exchange [4]. On the other hand, valence band exchange ($p-d$ exchange, characterized by $J_{p-d} \sim \beta$) is dominated by the kinetic process and can be either AFM ($\beta < 0$), as it is for Mn-based II–VI DMS [4], or can be FM ($\beta > 0$), as was observed for Cr-based II–VI DMS [58–60].

For III–V DMS different types of Mn centers may give rise to different $s, p-d$ exchange. The $s-d$ exchange, being still one-center exchange, is expected to be FM and not very dissimilar from that for II–VI DMS [4]. For $p-d$ exchange the situation is different. In the case of $A^-(d^5)$ center $p-d$ exchange should be AFM, as it was for all Mn-based II–VI DMS [1, 2]. On the other hand, for $A^0(d^5 + h)$ the situation is more complex, since except AFM exchange channels, the same as for $A^-(d^5)$, the spin polarized empty state of the bound hole provides additional, FM exchange path [61]. The final character of $p-d$ exchange would then result from the competition of AFM and FM channels [61].

Some information concerning the energy structure can be provided by photoemission experiments. Such study was done for GaMnAs. The Mn core level photoemission (XPS [51]) spectra were analyzed with the so-called cluster interaction model, taking into account different many-electron configurations. It was found that the experimental data could be equally well described assuming either $Mn^{2+}(A^-)$ or $Mn^{3+}(A^0)$ as dominant centers [51, 62]. On the other hand, the density of states resulting from Mn doping was calculated in coherent potential approximation [63] and first principles supercell method [64].

The most precise information about $s, p-d$ exchange was obtained by interband spectroscopy. For bulk GaMnAs crystals, with a low Mn concentration ($x < 0.001$) exciton splits in a FM way, suggesting FM $p-d$ exchange. The observed sense of bands splitting was interpreted as dominance of FM $p-d$ exchange channels of A^0 over the AFM paths of A^0 and A^- [52]. The exciton splitting is well parametrized by macroscopic magnetization. From $\Delta E \sim M$ dependence (the standard formula for the transitions in the center of the Brillouin zone [56]: $\Delta E = (N_0\alpha - N_0\beta)x\langle S \rangle$) exchange parameter $N_0\alpha - N_0\beta = -2.3$ eV was estimated. Assuming $N_0\alpha = +0.2$ eV the $p-d$ exchange integral was obtained $N_0\beta = +2.5$ eV, which is not very different in magnitude from the parameters for II–VI DMS.

In the case of GaMnAs epilayers, where only A^- centers were visible and thus AFM $p-d$ exchange could be anticipated, the first experiments seemed to corroborate the expectations [65]. On the other hand, the direct transmission experiment revealed a different absorption edge splitting [66]. The absorption edge

was very broad and no excitonic structure was visible. The sense of the edge splitting is the same as was for bulk GaAs:Mn [52], i.e. it is of FM-type. This result contradicts the reflectance magnetic circular dichroism (MCD) observation [65]. The edge splitting closely follows magnetization of the epilayer, showing a typical DMS behavior.

The above discussion of the magnetooptic data assumed direct transitions in the center of the Brillouin zone. This is correct for bulk GaAs:Mn crystals, for which a hole concentration is relatively low. However for the epilayers with the hole concentration ranging between 10^{18}–10^{20} cm^{-3}, the fact that the top of the valence band is empty, must be taken into account. Consequently, the Moss–Burstein shift of the absorption edge becomes sizable and is different for transitions originating from different valence subbands split by s, p–d exchange interaction. It appears that in such case, for FM s–d exchange ($N_0\alpha > 0$) and AFM p–d exchange ($N_0\beta < 0$), the edge splitting is of FM-type [66]. In other words, due to the Moss–Burstein shift the sense of the edge splitting is opposite to the sign of $N_0\beta$ (assuming typical values of $N_0\beta$ and $N_0\alpha$). We stress that in this model the Moss–Burstein shift is the primary reason of this splitting inversion. The role of p–d interaction is rather to polarize the hole subbands, which differentiate the Moss–Burstein transition energies. Only if the valence band exchange energy overcomes the Fermi energy E_F, the regular (AFM for $N_0\beta < 0$) splitting pattern is restored. Although the presented model seems to recover the essence of the actual situation for p-type GaMnAs, there are still some difficulties with it. In particular it does not take into account the band tailing, highly probable in a heavily doped material. Verification of the model (and determination of $N_0\beta$) can hardly be done due to rather a large uncertainty of hole concentration of the studied epilayers.

The FM-type splitting of the absorption spectrum was also observed for transmission MCD experiments [67, 68]. It was suggested in Ref. [68] that the positive peaks in MCD spectra reflect Zeeman splitting of the Mn intraion transitions. Only a negative contribution to MCD around 1.6 eV, derived from MCD temperature dependence, was ascribed to AFM p–d exchange effects [68]. The Moss–Burstein shift was not taken into account and no quantitative analysis was presented [68].

Another important example of s, p–d exchange effect is Faraday rotation [69].

The information about p–d exchange in GaMnAs was derived also from other experiments. Transport measurements data yielded an absolute value of $|N_0\beta| = 3.3$ eV [21]. The analysis of magnetic data (Curie critical temperature T_C) allowed one to estimate the absolute value of $|N_0\beta|$ between 1.0–1.25 eV [70]. The parameters obtained from the core-level photoemission data analysis mentioned above [51] gave $N_0\beta = -1.2$ eV, if A^- configuration was assumed.

In summary, s, p–d exchange interaction in III–V DMS produces large magnetooptical effects. These effects are parametrized by magnetization of the crystal, similarly as it was for II–VI DMS.

5. Magnetic properties and d–d exchange interaction

The coupling between Mn ions (resulting from d–d exchange interaction) is one of the most interesting features of III–V DMS. Before proceeding to this

subject we briefly consider magnetic properties of isolated (noninteracting) Mn centers A^- and A^0.

As we discussed above the ground state of $A^-(d^5)$ center is a spin sextet ($S = 5/2$) and orbital singlet ($L = 0$). The excited states are well above the ground state so one should expect paramagnetic (PM) behavior of a typical single multiplet, whose magnetization is described by a classical Brillouin function. This seems to be the case at least for very low Mn concentrations, where Mn–Mn coupling can be neglected. The experimental data are pretty well described by the Brillouin function with $S = 5/2$ [71]. We note that EPR performed for these samples revealed only A^- Mn centers.

For the systems with a higher Mn concentration (of the order of molar percent) a coupling between Mn ions may be strong enough to be reflected by basic magnetic properties. We recall that in GaMnAs and InMnAs epilayers only A^- centers were visible, so in analogy to Mn-based II–VI DMS one may expect AFM coupling between Mn ions, driven by superexchange mechanism [4]. Indeed some InMnAs epilayers (n-type) show AFM Mn–Mn coupling, as demonstrated by negative Curie–Weiss temperature of susceptibility [12]. The d–d exchange integral was estimated to be $J_{NN} = -1.6$ K, which is less than for the corresponding II–VI DMS [12]. On the other hand, for some other (p-type) InMnAs and GaMnAs epilayers FM interaction between Mn ions was observed [20, 30, 17, 18, 23]. Magnetization saturates much faster with magnetic field than expected for isolated ions, which is a signature of FM coupling between the ions. Pronounced hysteresis loops were also observed with some anisotropy depending on the orientation of magnetic field relatively epilayer plane [23, 24], suggesting the existence of a long ranged FM phase. A temperature dependence of magnetization measured at low magnetic fields also shows a typical FM critical behavior. The FM critical temperature increases with increasing Mn concentration to the maximum value of 110 K reached for $x = 0.05 \div 0.06$, then decreases for still higher concentrations. This behavior is closely related to the hole concentration of the crystal [21], strongly suggesting the carrier induced mechanism for the FM d–d exchange.

The current understanding of the d–d exchange interaction is the following. For the materials with low carrier concentration (e.g. semiinsulating epilayers) AFM superexchange, typical of Mn^{2+} ions, dominates the magnetic properties. Paramagnetic behavior (with weak AFM coupling) is then observed. For the systems with high holes concentration carrier induced FM interaction becomes important and may override AFM superexchange, leading to FM order. We note that a similar situation was observed for Mn-based IV–VI DMS, which show FM or paramagnetic behavior depending on the hole concentration [7]. Also for quantum wells fabricated of Mn-based II–VI DMS (CdMnTe or ZnMnTe), FM interaction arises if the wells are filled with holes [8]. There were essentially two microscopic mechanisms proposed to explain FM in III–V DMS. The first one was classical RKKY exchange [72, 73], where the orientation of magnetic ions' spins is provided by s- (or p-) -d exchange interaction with mobile carriers. Briefly speaking one ion polarizes the spin of the carrier, then the spin polarized carrier orients the spin of the second magnetic ion. This means that RKKY interaction will be effective as long as the mean free path is larger than the mean distance between

the ions [74]. It is worthwhile to note that RKKY $d-d$ exchange does not depend on the sign of $s, p-d$ exchange and is more effective for the heavy carriers (due to a larger density of states). Although the situation in III–V DMS does not match the RKKY assumptions, this model was widely used to interpret the experimental data. In particular T_C calculated basing on RKKY model agrees reasonably well with the experimental phase diagram [21]. This may suggest that RKKY is a good staring point to understand ferromagnetism of III–V DMS. An alternative approach to describe $d-d$ interaction in III–V DMS was based on Zener model [75]. This approach in semiconductors is equivalent to RKKY model, but enables one to take into account the details of the band structure, in particular spin–orbit interaction [75]. The differences in band structures of different III–V (and II–VI) materials result in different maximal critical temperatures T_C. In particular it is predicted that ambient temperature ferromagnetism may be reached in GaN and ZnO [75].

The absence of FM in n-type materials may be understood on the grounds of RKKY/Zener models as the density of states of electrons is smaller than that of holes and $s-d$ exchange integral is typically a few times smaller in magnitude than $p-d$ integral. Consequently, the carrier induced ferromagnetic exchange is not large enough to override AFM superexchange.

Another approach to the carrier induced ferromagnetism is a double exchange (DE) mechanism. Classically DE may be expected for the system of magnetic ions with different valency. The virtual jumps of electrons from one ion to the empty states of the other ion yields a coupling between the ions. The DE approach is useful in the case of narrow bands, as compared to $s, p-d$ exchange. For InMnAs it was proposed to start with the d band formed by manganese impurities. DE in this case essentially means that the band energy of the FM state is lower than that of the AFM state, provided there is a sufficient number of holes in the band. Using the Korringa–Kohn–Rostoker coherent potential approximation and local density approximation, the density of spin polarized states was calculated [63]. It was found that the FM state is indeed stable.

The above models although not exactly applicable to III–V DMS are probably reasonable outermost approaches to the proper solution of the real problem. The experimental information about the character of the holes would be important for developing the final model.

6. Transport properties

As we noted before MBE grown III–V DMS usually reveal a good conductance, which is quite sensitive to the growth condition, in particular to the growth temperature. Tuning the growth conditions it is possible to have epilayers with the same Mn content x, but very different carrier concentrations [17]. The details of this problem were discussed elsewhere [11, 15, 19, 24, 25]. Typically, the carrier concentration is closely related to the Mn concentration, since Mn acts as an acceptor. This may be exemplified by n-type InMnAs, where an initially high concentration of electrons decreases by about three orders of magnitude with Mn doping [12]. Compensation of electrons by Mn acceptors was proposed to explain

this behavior. On the other hand, for p-type GaMnAs hole concentration increases with increasing x up to about 0.05–0.06 [21].

The temperature dependence of resistivity of as-grown p-type GaMnAs shows that for low Mn concentrations ($x < 0.03$) this material behaves as a regular semiconductor [31]. The activation energy was found to be about 70 meV (in reasonable agreement with 113 meV of the A^0 binding energy [32]) for the lowest x, then decreasing with increasing x. With increasing Mn content the system undergoes nonmetal-to-metal transition. For $0.03 < x < 0.05$ resistivity is very weakly temperature dependent, revealing a hump around FM–PM transition temperature. The hump was related to scattering of carriers by magnetic spin fluctuations around $T_{\rm C}$ via p–d exchange interaction and was also observed for magnetic metals and magnetic semiconductors [76–78]. For the samples with $x > 0.05$ the hump at $T_{\rm C}$ is still visible, but below $T_{\rm C}$ resistivity increases rapidly. It was suggested that this "reentrant" non-metallic behavior results from localization of holes due to increasing disorder for high Mn concentrations.

For all GaMnAs epilayers pronounced negative magnetoresistance was observed, being the largest for reentrant, non-metallic samples [31, 21]. The interpretation of this magnetoresistance was based on the assumption that the holes are mostly scattered by Mn impurities. Aligning the spins of Mn ions leads to the reduction of the scattering and then resistivity. For metallic systems magnetoresistance at PM temperature range, where scattering on critical magnetization fluctuations could be neglected, was analyzed using the spin disorder model [21].

As for the magnetoresistance for reentrant non-metallic systems there were two possible scenarios proposed. The first one was based on a magnetic polaron picture, where the negative magnetoresistance results from smearing the polaronic cloud of Mn ions with increasing magnetic field. It is also correlated with PM contribution to magnetization of the system. The second model is based on Anderson localization. Applied magnetic field splits a mobility edge, which reduces the localization length, leading to a negative magnetoresistance [31].

Another useful transport quantity widely studied for III–V DMS was Hall resistivity $\rho_{\rm H} = U_{\rm H}/I_x$, where $U_{\rm H}$ is Hall voltage and I_x is the current flowing along the epilayer. It was found that except for normal Hall contribution proportional to magnetic field B, there is also anomalous component proportional to magnetization [21, 24, 79]: $\rho_{\rm H} = R_0 B + R_a M$. Separate measurements showed that R_a is proportional to the sheet resistivity of the epilayer ($= U_x/I_x$), indicating that skew scattering is responsible for anomalous term [79]. Since a typical hole concentration is high, the normal term is small as compared to the anomalous one. The latter one dominates $\rho_{\rm H}$, which then is proportional to M and can be used as a convenient measure of the magnetization.

Transport properties of p-type InMnAs are essentially similar to those of GaMnAs [20, 30].

Finally, we note that the hole concentration determined for the epilayers was found on the level of 30% of Mn concentration, which means that if all Mn centers act as acceptors, about 70% of them must be compensated by donors. The most probable candidate for such donor is As antisite, however some experimental observations contradict such supposition.

7. Other issues

The discussion in preceding sections, although concerning epilayers, was in fact devoted to "bulk" properties of III–V DMS. However, these materials can be also used to fabricate quantum structures. This possibility is especially attractive since it allows one to integrate two broad subjects: semiconductor physics with cooperative magnetic phenomena, both in nanoscale. Below we give a few examples of the problems where the nanoscale geometry plays the key role.

As the first example we consider photo induced FM in InMnAs/AlGaSb heterostructures [13]. It was found that illumination of suitable heterostructures results in ferromagnetism of InMnAs layer. The effect was explained in terms of hole induced FM, where holes were photo generated and accumulated in InMnAs layer, triggering FM, while photo created electrons were removed away by the electric field at the interface. Although this effect has not been fully understood yet, it opens a very fascinating possibility of controlling magnetic properties of the system by light.

The coupling between magnetic GaMnAs layers was investigated for a series of trilayer system, consisting of GaMnAs layers separated by nonmagnetic GaAlAs layer [81]. The experiments were performed as a function of nonmagnetic layer thickness, to study the distance dependence of the coupling. It was found that the coupling between the magnetic layers is FM and strongly depends on the barrier height [81]. It was then suggested that the inter layer coupling is induced by the holes in GaAlAs. Quantitative understanding of the microscopic mechanism behind the coupling awaits a further study, both experimental and theoretical.

III–V DMS were successfully used to fabricate resonant tunneling diodes [82, 83], which can be used for spectroscopy of electronic states. The valence band $p-d$ exchange induced splitting was observed as splitting of resonant peaks in current–voltage characteristics. A spontaneous splitting of both heavy and light holes states can be observed in the temperature range where GaMnAs is FM. The details of the splitting were interpreted using the calculated band structure of GaMnAs [84].

Recently III–V DMS have been integrated with II–VI DMS to study proximity effects [85]. Antiferromagnetic MnTe was deposited on the top of GaMnAs, with GaAs spacer of varying thickness. A substantial increase in coercive field was found [85].

8. Concluding remarks

Magnetic semiconductors based on III–V compounds refresh typical problems of classical II–VI DMS (e.g. s, $p-d$ exchange). On the other hand, they offer new opportunities, such as interplay of ferromagnetism controlled by carrier concentration and semiconductor properties. It should be stressed that ferromagnetism can be observed up to rather high temperatures. Moreover, these systems can be fairly easily used for fabrication of quantum structures. All these features make III–V DMS very interesting for both fundamental physics and applications. The devices based on III–V DMS will probably be available in the near future.

Acknowledgments

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