Electronic energy levels, wavefunctions and potential landscape of nanostructures probed by magneto-tunnelling spectroscopy

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Abstract. We create electrostatically induced quantum dots by thermal diffusion of interstitial Mn out of a p-type (GaMn)As layer into the vicinity of a GaAs quantum well. This leads to the formation of deep, approximately circular and strongly confined dot-like potential minima in a large mesa diode structure. The minima are formed without need for advanced lithography or electrostatic gating. Using fields of up to 30 T, magnetotunnelling spectroscopy of an individual dot reveals the symmetry of the electronic eigenfunctions and, for the approximately circular dots, a rich spectrum of Fock-Darwin-like states with an orbital angular momentum component \(|l_z|\) ranging from 0 up to 11. We find that a small fraction of the dots has elongated potential minima, giving rise to quenching of the orbital angular momentum of the electronic eigenstates. By developing a model to describe the diffusion of the Mn interstitial ions, we determine the electrostatic potential landscape in the quantum well and hence the distribution of dot shapes and sizes. This is in a good agreement with our experimental data.

1. Introduction and brief history of magneto-tunnelling spectroscopy

The combination of high magnetic fields and quantum tunnelling provides a powerful tool for elucidating the nature of the quantized states of both free and bound electrons and holes in semiconductor materials, device and nanostructures. In magnetotunnelling spectroscopy (MTS) experiments, an applied bias is used to resonantly tune the energy of a charged carrier which tunnels through a barrier into a quantum state. When a magnetic field is applied in the plane of the barrier, the tunnelling electron or hole acquires an in-plane momentum due to the action of the Lorentz force. Thus the combination of applied bias and magnetic field can be used to control both the energy and the in-plane wavevector of a carrier when it enters the quantum state. The concept of MTS was developed from early studies of magneto-electric skipping states at a tunnel barrier interface [1] and from measurements of the change in the current-voltage characteristics, \(I(V)\), of a resonant tunnelling device due to a strong magnetic field applied in the plane of the quantum well [2]. It was then used to measure resonant band anticrossing effects in the valence [3,4] and conduction bands [5,6] of quantum
wells, thus providing detailed plots of the energy-wavevector dispersion relations, $\varepsilon(k)$, of holes and electrons. In addition to the study of the extended states of free carriers, MTS has also been used to map out in $k$-space the probability distribution function $|\psi(k)|^2$ of the bound electronic states, including the ground and excited states of hydrogenic donors [7], quantum wires [8] and self-assembled quantum dots [9-11]. Since the wavefunction of a stationary state is real, it is therefore possible to deduce $\psi(k)$ and hence determine the form of the real space wavefunction $\psi(r)$ in these types of quantum structure. Magnetocapacitance spectroscopy, a variant of MTS, has recently been used to probe the wavefunctions of many-electron states of InAs quantum dots [12]. The MTS technique is able to probe the eigenfunctions and eigenstates of nanostructures which are buried deep below the surface of a functional semiconductor device. For this reason it complements scanning tunnelling microscopy, which can only access atoms and eigenstates at or very close to the surface of a solid.

Here we describe how MTS can be used to study the electronic properties of electrostatically-induced quantum dots (QDs) [13,14]. We show how studies of the dependence of the tunnel current on magnetic field applied parallel and perpendicular to the barrier plane ($xy$) can be combined to provide detailed information about the electronic eigenstates. We make these dots by post-growth annealing of a $p-i-n$ diode in which the $p$-layer is composed of ferromagnetic (GaMn)As with 5% Mn and the undoped intrinsic “$i$” layer contains an AlAs/GaAs double barrier resonant tunnelling structure. For a narrow range of annealing conditions, it is possible to diffuse doubly-ionised Mn interstitial ($\text{Mn}^{2+}$) donor ions out of the (GaMn)As surface layer into an undoped GaAs layer adjacent to the quantum well structure. The random clustering of small numbers (typically $\lesssim 10$) of the Mn$^{2+}$ ions modifies the electrostatic potential in the well, each cluster giving rise to deep and approximately parabolic potential energy minima which can quantum confine tunnelling electrons on a length scale of $\sim 10$ nm [13,14].

MTS reveals the presence of dots with approximately circular symmetry, in which the electron eigenstates in high magnetic fields approximate to the Fock-Darwin model [15]. Sharp resonant tunnelling peaks with the $z$-component of angular momentum ranging from zero up to 11 are observed. In addition, we also find that some of the dots are elongated, and the orbital momentum is quenched. Wavefunction images of the dot eigenstates are measured by studying the variation of the tunnel current as a function of the in-plane magnetic field. We compare our experimental data with a theoretical model which describes the thermal diffusion process, the potential landscape created by the diffused Mn$^{2+}$ ions and the nature of the electronic eigenstates of the dots.

Mn interstitials form in (GaMn)As when the Mn concentration exceeds $\sim 2\%$. They are doubly ionised donors, $\text{Mn}^{2+}(3d^5)$, and inhibit ferromagnetism as they compensate the itinerant holes introduced by substitutional $\text{MnAs}$ acceptors [16,17]. Thermal annealing of (GaMn)As is an effective means of increasing its Curie temperature and electrical conductivity by out-diffusion of the compensating Mn donors to the surface of the heterostructure [17]. We use controlled annealing to create QD-like potential minima in $p-i-n$ resonant tunnelling diodes (RTDs) containing a (GaMn)As top layer, grown by molecular beam epitaxy on (001) n$^+$-GaAs substrates.

2. Details of the heterostructure and the effect of annealing

We focus on high magnetic field studies of a structure with the following composition, in order of growth on a (100) n$^+$ GaAs substrate: a 300 nm layer of n$^+$-GaAs Si-doped to $2\times 10^{18}$ cm$^{-3}$; 100 nm of n-GaAs doped to $2\times 10^{17}$ cm$^{-3}$; an undoped central intrinsic region comprising a 20 nm GaAs layer, a 5 nm AlAs tunnel barrier, a 6 nm GaAs QW, a 5 nm AlAs tunnel barrier and a 10 nm GaAs layer, and,
finally, a 50nm capping layer of p\(^+$\)-(GaMn)As with 3% Mn. The (GaMn)As layer was grown at 250°C, the others at 600°C. The epilayers were processed into 200 \(\mu\)m diameter mesa diodes, shown schematically in Figure 1(a). These devices emit bright electroluminescence from the QW in forward bias above the flat band conditions [18]. A schematic band diagram of the device at zero bias is shown in Figure 1(b).

Prior to annealing, the forward bias current flowing through the device increases rapidly around the flat band condition, \(V \approx V_{FB} = 1.41\) V, rising to a peak at 1.8 V, which corresponds to resonant electron tunnelling through the lowest (\(E1\)) subband of the two-dimensional (2-D) conduction band QW. No current is detectable above the background noise level (< 0.3 pA) in the as-grown mesas for \(V < 1.3\) V. However, following annealing at 150°C for 3 hours, sharp peaks appear in \(I(V)\) below 1.3 V with peak heights in the range \(\sim 10-100\) pA. We attribute these peaks to tunnelling into discrete quantum states arising from the formation of deep potential minima as shown schematically in Figure 1(c). Following this type of low temperature annealing, small clusters of diffused Mn\(_i\) ions form in the undoped GaAs region between the (GaMn)As layer and the upper AlAs barrier. Since each ion is doubly charged (+2e), this clustering gives rise to deep minima in the potential energy profile at the central plane of the QW. The deepest minima are formed by clusters containing typically 5-10 closely-separated Mn\(_i\) ions (all within \(\sim 10\)nm). The measured thermal broadening of the low voltage threshold of each current peak between 0.3 and 20 K confirms that the resonances are due to resonant tunnelling into a single quantised energy level by electrons close the Fermi level, \(E_F\), of a thermalised degenerate electron gas in the n-GaAs emitter. These measurements also determine the fraction of applied voltage, \(f = 0.65\pm0.05\), dropped between \(E_F\) and the level [19]. This \(f\)-value indicates that the states through which electrons tunnel are spatially confined in the QW between the two AlAs barriers; the energy of a particular state is given by \(eV + a\), when \(a\) is a constant.

Higher temperature (up to 200°C) or longer annealing (>3 hours) leads to merging of the sharp peaks into an increasingly broad and strong shoulder in \(I(V)\). We attribute this to the formation of additional current pathways arising from diffusion of increasing numbers of Mn\(_i\) ions from the (GaMn)As towards the QW. This conclusion is supported by measurements on control samples, in

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Figure 1

**a)** Schematic showing the layer structure of a (GaMn)As \(p-i-n\) diode and a layer of diffused Mn\(_i\) donors.

**b)** Calculated conduction band diagram of our device before (black) and after (blue) annealing.

**c)** Potential energy profile, \(U_{QW}(x,y)\), in the central QW plane, and schematic of an electron tunnelling from the n-GaAs layer into quantised states of a minimum of \(U_{QW}(x,y)\).
which a Be- or C-doped p-GaAs capping layer replaces the (GaMn)As: their $I(V)$ are unaffected by annealing for 24 hours at 250°C, due to the much smaller diffusion coefficient of these dopants compared to Mn interstitials.

3. Experimental results: magnetotunnelling spectra in fields up to 30T

To understand the nature of the quantum states associated with the sharp tunnelling resonances, we first examine the effect of a magnetic field, $B_z$, applied perpendicular to the QW plane. Figure 2(a) shows a grey-scale plot of differential conductance, $dI/dV$, versus $B_z$ for a sample annealed at 150°C for 3 hours (a darker shade corresponds to higher conductance). The lowest-energy peak does not split, but shifts to higher bias, consistent with the diamagnetic shift of a 1s-like orbital ground state. In contrast, the higher bias peaks reveal a rich orbital Zeeman splitting pattern. Figure 2(a) also plots the calculated $B_z$-dependence of the Fock-Darwin spectrum for a 2-D parabolic potential [19]. This provides a quantitative fit to our data with only one adjustable parameter, $\hbar\omega_0 = 22 \pm 2$ meV, the characteristic energy spacing of the Fock-Darwin levels at $B_z = 0$. The other parameters are the electron effective mass in GaAs and leverage factor $f$.

![Figure 2](image_url)

(a) Grey-scale plot of differential conductance $dI/dV$ at $T = 2K$ versus $B_z$ up to 28T for a relatively symmetric nanoelectrostatic QD. Red lines represent the fit to the Fock-Darwin spectrum.

(b) Numerical simulation of the electrostatic potential created by randomly distributed nanoclusters of diffused Mn ions for $d = 18$nm.

(c) Blue solid curves: $B_z$-dependences of the energy spectrum calculated for the deep potential minimum in the area marked by the red square in plot (b). Red dashed lines: Fock-Darwin spectrum.

The emergence, at high field ($B_z > 16$ T), of a series of equally-spaced peaks, which shift to lower energy and become more closely spaced with increasing $B_z$, is a characteristic feature of FD states. At high $B_z$, these evolve into nondegenerate states of the lowest Landau level, which skip around equipotential contours of the confining potential with different quantised angular momenta, $l_z$; we observe $|l_z|$ values from 0 to 11 (Fig. 2a). In the limit of high $B_z$, these states correspond to states of the lowest Landau level, modified by the presence of the near-parabolic confining potential. A comparison of our data with the FD model reveals that the confining potential does not have exact
circular symmetry: the orbital degeneracy of the first two excited states, $2p_z$, is lifted even at $B_z = 0$ (see the split peaks at $V \sim 1.29$ V). This lowered symmetry also explains the lifting of the three-fold orbital degeneracy of the next set of excited states around $V = 1.325$ V and the level anti-crossings, e.g. that at $V = 1.31$ V and $B_z = 8$ T.

From our measurements, we deduce that the electrons are tunnelling through the bound states of a deep and approximately parabolic circular potential well, see Figure 1(c). To understand how such a potential can be produced by low temperature annealing, we use Fick’s law to calculate the density distribution of Mn$^{2+}$ ions that have diffused out of the p-(GaMn)As, assuming a constant surface concentration of Mn$_i$ at the (GaMn)As/GaAs interface.

The band bending along $z$ resulting from the diffused Mn$_i^{2+}$ ions is calculated from Poisson’s equation and shown in Figure 1(b). Although the conduction band edge $E_c$ in the GaAs spacer layer is lowered relative to the unannealed case, it remains well above the Fermi energy $E_F$, so that the Mn$_i^{2+}$ donors remain ionised. Despite the electric field in the intrinsic region of the diode, the barrier height, $Q$, for hopping of Mn$_i$ ions between interstitial sites is only slightly reduced (<5%) by electrostatic effects. This is supported by experiment: we observe no change in the diffusion rate of Mn$_i$ for annealing at 150°C in the presence of applied voltages of ±1 V.

We simulate numerically the distribution of Mn$_i$ ions neglecting Coulomb interactions between them. This is a reasonable approximation since the Mn$_i$ density in the GaAs spacer is relatively low, changing from $\sim 10^{19}$ cm$^{-3}$ at the (GaMn)As interface to effectively zero at the AlAs interface (corresponding to a mean Mn$_i$ separation $>5$nm and a Coulomb interaction energy much less than $Q$). Our simulated positions of individual Mn$_i$ in the $xy$-plane are defined by random numbers corresponding to “white noise” of uniform distribution, with the ion density along the growth axis $z$ given by the Fick law. The simulations use $3 \times 10^5$ Mn$_i^{2+}$ ions occupying a volume of $5 \times 5 \times d$ $\mu$m$^3$, where $d$ is the distance from the (GaMn)As/GaAs interface to the central QW plane. Figures 1(c) and 2(b) show the resulting electronic potential energy $U_{QW}(x,y)$ in the middle of the QW, for a central area of 0.3 $\times$ $0.3$ $\mu$m$^2$, over which edge effects can be neglected. The potential energy contours in Figures 2(b) reveal a complex landscape. This arises from random spatial variations in the density profile of diffused Mn$_i$ with nanoscale regions (“clusters”) extending over ~10 nm, where the local density of Mn$_i$ considerably exceeds the mean value. The “clusters” giving rise to the deepest potential minima typically contain up to ~10 randomly-placed Mn$_i$ ions and form in the GaAs layer just below the (GaMn)As layer. A deep minimum in $U_{QW}(x,y)$ directly below such a cluster can be seen to left of center in Fig. 2(b). The lowest energy quantised states of this potential minimum are $\sim 0.3$ eV below $E_c$. Hence they provide resonant channels for electron tunnelling at bias voltages far below the flat band condition and give rise to the sharp peaks in $I(V)$. By solving numerically the 2-D Schrödinger equation of an electron in this minimum as a function of $B_z$, we obtain a calculated magnetospectrum shown in Figure 2(c). This is in good qualitative agreement with the measured spectrum in Figure 2(a).

The spatial forms of the QD wavefunctions are related directly to the potential landscape by Schrödinger’s equation. By measuring a tunnel current through a particular QD as a function of $B_{xy}$ aligned different directions in the $xy$-plane, we obtain a spatial map of the probability density $|\psi(k)|^2$ of an eigenstate in the $k_x - k_y$ plane of momentum space. It is reasonable to assume that the $z$-motion is fully quantised into the ground state of motion along this direction and that the wavefunction can be separated into $z$- and $xy$-parts. The Lorentz force on the tunnelling electrons allows us to tune their in-plane momentum, $\hbar k$, according to the relation $k = -es \times B/\hbar$, where $s = 10 \pm 1$nm is the length of the tunnelling path from the emitter into the bound states of the QD. Whereas the ground state wavefunction has approximately circular symmetry, the wavefunction maps of the first two excited states have the lobed character of $2p_z$ and $2p_x$ orbitals rather than the toroidal shape of degenerate $2p_z$ orbitals. This is consistent with the observed zero field energy splitting of the $2p$-like states in Figure
2(a) and provides additional evidence that the symmetry of the confining potential is lower than that of the FD model.

Figure 3 plots along the symmetry axes \( k_x \) and \( k_y \) of \( |\psi(k)|^2 \) at \( B_{xy} \) up to 30 T for the 1s-like and 2\( p_{x,y} \) eigenstates of a deep potential minimum. Blue circles: data points; red curves: fits to simple harmonic oscillator potential with \( h\omega_0 = 22 \) meV. The inset shows the circular symmetry of the 1s-like ground state wavefunction in the \( xy \)-plane.

Figure 3 probes the \( |\psi(k)|^2 \) probability density functions of the almost circular symmetric 1s state (see inset Fig. 3) and of the non-degenerate 2\( p_{x,y} \) orbitals along their respective symmetry axes using fields up to 30T. A fit to the simple harmonic oscillator (SHO) approximation gives \( h\omega_0 = 24\pm2 \) meV, in agreement with the value 22 meV obtained independently from the data in Figure 2(a). However, the measured \( |\psi(k)|^2 \) of the 2\( p_{x,y} \) states also have a significant amplitude at \( k_{xy} \sim B_{xy} = 0 \), in contrast to the form expected for single particle SHO-states. We attribute this feature to the finite spread of \( k \)-states in the degenerate Fermi sphere of the emitter and to the electron-electron interactions between the tunnelling electron and nearby electrons in the emitter Fermi sea [20-22].

4. Observation of elongated quantum dots with quenched angular momenta

Many of the deep quantum dots that we have created and studied using our annealing method approximate quite well to Fock-Darwin states (Fig. 2a), indicating that they have approximately circular symmetry. However, for some of the dots the absence of orbital Zeeman splitting in the MTS spectra with \( B||z \) indicates that their orbital angular momentum is quenched even in fields of 30T and hence that the confining potential is far from circular. The presence of strongly elongated deep potential minima is evident from one of our simulations shown in Figure 4(a). Close to the minimum of the potential, the equipotentials are far from circular. Figure 4(b) shows the corresponding calculated energy spectra for the lowest energy levels of this confining potential. The energies of the lowest eigenstates are equally spaced to a reasonable approximation, indicating a harmonic potential. However, they have only weak magnetic field dependences indicating that orbital angular momentum of the 2p-like levels etc. is quenched even at fields of ~20 T. Figure 4(c) shows a grey scale conductance plot of the measured magnetotunnelling spectrum for such an elongated dot.
Figure 4

(a) An elongated electrostatic potential minimum created by randomly distributed nanoclusters of Mn ions, as obtained from our numerical simulations. 
(b) $B_z$-dependences of the energy spectrum calculated in the area marked by the red square in plot (a). 
(c) Grey-scale plot of $dI/dV$ at $T = 2K$ versus $B_z$ up to 28T for an elongated nanoelectrostatic QD.

Figure 5 is assembled from our numerical simulations by analysing the characteristics of 80 deep potential minima such as that shown in Figure 4(a). We use these to plot the probability of finding a dot with a particular value of the parameter $\omega_2/\omega_1$. The potential minima approximate well to $m_e^*(\omega_1^2x^2+\omega_2^2y^2)/2$, where $\omega_1$ and $\omega_2$ characterise an elliptical contour. It can be seen from the Figure 5 that only a small fraction of the dots have anisotropy ratio $\omega_1/\omega_2 < 0.6$. We measured in detail the magnetotunnelling spectra of 20 deep quantum dots. Most of these dots have energy spectra similar to the Fock-Darwin model, thus indicating an approximately circular symmetric potential. Only two of the measured samples have energy spectra that indicate large deviations from circular symmetry, as for the case shown in Figure 4, in good qualitative agreement with our model calculations.
Finally, we address the question of what happens to the electrons after tunnelling from the n-type emitter into one of the deep potential minima. The typical current at a resonant peak (~10-100 pA) is consistent with electrons tunnelling out of the minima across the band gap and into the empty states at the top of the valence band in the GaMnAs layer. Future tunnelling experiments could help elucidate the nature of these states near the valence band edge of GaMnAs [18,24].

5. Conclusions
We have used high magnetic fields combined with resonant-tunnelling spectroscopy to study electronic properties formed by the controlled diffusion of doubly charged Mn$^{2+}$ donor ions in $p-i-n$ resonant-tunnelling-diodes in which the capping $p$-layer is ferromagnetic (GaMn)As. Random clusters of these ions give rise to deep potential minima in the plane of the quantum well of the device. We observe a Fock-Darwin-like spectrum for the eigenstates of the minima with approximately circular symmetry, but we also observe elongated potential minima in which the orbital angular momentum of the bound electron states is quenched. These experiments provided insights into these “electrostatically formed” quantum dots and also into the nature of the diffusion process of Mn interstitial donors, which in turn has led on to our development of a new method of making submicron-size light-emitting diodes by means of laser assisted diffusion of Mn$^{2+}$ in $p-i-n$ diodes [24].

References

[1] Snell B R, Chan K S, Sheard F W, Eaves L, Toombs G A, Maude D K, Portal J C, Bass S J, Claxton P, Hill G and Pate M A 1987 Phys. Rev. Lett. 59 2806
[2] Leadbeater M L, Eaves L, Simmonds P E, Toombs G A, Sheard F W, Claxton P A, Hill G and Pate M A 1988 Solid-State Electron. 31 707
[3] Hayden R K, Maude D K, Eaves L, Valadares E C, Henini M, Sheard F W, Hughes O H, Portal J C and Cury L 1991 Phys. Rev. Lett. 66 1749
[4] Gennser U, Kesan V P, Syphers D A, Smith III T P, Iyer S S and Yang E S 1993 Appl. Phys. Lett. 63 545
[5] Endicott J, Patanè A, Ibañez J, Eaves L and Bissiri M, 2003 Phys. Rev. Lett. 91 126802
[6] Patanè A, Endicott J, Ibañez J, Brunkov P N, Eaves L, Healy S B, Lindsay A, O’Reilly E P and Hopkinson, M 2005 Phys. Rev. B 71 195307
[7] Sakai J-W, Fromhold T M, Beton P H, Eaves L, Henini M, Main P C, Sheard F W and Hill G 1993 Phys. Rev. B 48 5664
[8] Beton P H, Wang J, Mori N, Eaves L, Main P C, Foster T J and Henini M 1995 Phys. Rev. Lett.
[9] Vdovin E E, Levin A, Patanè A, Eaves L, Main P C, Khanin Y N, Dubrovskii Y V, Henini M and Hill G 2000 Science 290 122
[10] Patanè A, Hill R J A, Eaves L, Main P C, Henini M, Zambrano M L, Levin A, Mori N, Hamaguchi C, Dubrovskii Y V, Vdovin E E, Austing D G, Tarucha S and Hill G 2002 Phys. Rev. B 65 165308
[11] Bester G, Reuter D, He Lixin, Zunger A, Kailuweit P, Wieck A D, Zeitler U, Maan J C, Wibbelhoff O and Lorke A 2007 Phys. Rev. B 76 075338
[12] Wibbelhoff O S, Lorke A, Reuter D and Wieck A D 2005 Appl. Phys. Lett. 86 092104
[13] Makarovsky O, Thomas O, Balanov A G, Eaves L, Patanè A, Campion R P, Foxon C T, Vdovin E E, Maude D K, Kiesslich G and Airey R J 2008 Phys. Rev. Lett. 101 226807
[14] Makarovsky O, Balanov A G, Eaves L, Patanè A, Campion R P, Foxon C T and Airey R J 2010 Phys. Rev. B 81 035323
[15] Johnson B L and Kirczenow G 2000 Europhys. Lett. 51 367
[16] Jungwirth T, Wang K Y, Masek J, Edmonds K W, Konig J, Sinova J, Polini M, Goncharuk N A, MacDonald A H, Sawicki M, Rushforth A W, Campion R P, Zhao L X, Foxon C T and Gallagher B L 2005 Phys. Rev. B 72 165204
[17] Edmonds K W, Boguslawski P, Wang K Y, Campion R P, Novikov S N, Farley N R S, Gallagher B L, Foxon C T, Sawicki M, Dietl T, Nardelli M B and Bernholc J 2004 Phys. Rev. Lett. 92 037201
[18] Thomas O, Makarovsky O, Patanè A, Eaves L, Campion R P, Edmonds K W, Foxon C T and Gallagher B L 2007 Appl. Phys. Lett. 90 082106
[19] Itskevich I E, Ihn T, Thornton A, Henini M, Foster T J, Moriarty P, Nogaret A, Beton P H, Eaves L and Main P C 1996 Phys. Rev. B 54 16401
[20] Geim A K, Main P C, La Scala N, Eaves L, Foster T J, Beton P H, Sakai J W, Sheard F W, Henini M, Hill G and Pate M A 1994 Phys. Rev. Lett. 72 2061
[21] Hapke-Wurst I, Zeitlter U, Frahm H, Jansen A G M, Haug R J and Pierz K 2000 Phys. Rev. B 62 12621
[22] Vdovin E E, Khanin Yu N, Makarovsky O, Dubrovskii Yu V, Patanè A, Eaves L, Henini M, Mellor C J, Benedict K A and Airey R 2007 Phys. Rev. B 75 115315
[23] Jungwirth T, Sinova S, MacDonald A H, Gallagher B L, Novák V, Edmonds K W, Rushforth A W, Campion R P, Foxon C T, Eaves L, Olejník E, Masek J, Yang S-R Eric, Wunderlich J, Gould C, Molenkamp L W, Dietl T and Ohno H 2007 Phys. Rev. B 76 125206
[24] Makarovsky O, Kumar S, Rastelli A, Patanè A, Eaves L, Balanov A G, Schmidt O G, Campion R and Foxon C T 2010 Advanced Materials 22 3176-3180