Measuring the spin polarization and Zeeman energy of a spin-polarized electron gas: Comparison between Raman scattering and photoluminescence

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We compare resonant electronic Raman scattering and photoluminescence measurements for the characterization of a spin-polarized two-dimensional electron gas embedded in Cd₁₋ₓMnₓTe single quantum wells. From Raman scattering by single-particle excitations in a zero magnetic field, we measure the Fermi velocity and then obtain the Fermi energy (as well as the electron density), which is comparable to that extracted from photoluminescence for moderate electron densities, assuming a bare band-edge mass. At large electron densities, the Fermi energies derived from Raman scattering and photoluminescence differ. For an applied in-plane magnetic field and zero wave vector transferred to the electron gas, Raman scattering spectra show peaks at both the Zeeman energy $Z$, resulting from collective excitations of the spin-polarized electron gas, and the one electron spin-flip energy $Z'$. Magneto-photoluminescence spectra show conduction band splitting that are equivalent to $Z$, suggesting that collective effects are present in the photoluminescence spectra. Assuming (as before) an uncorrected mass, the degree of spin polarization $\zeta$ determined from the magneto-photoluminescence lineshape is found to differ from that derived from the magnetic field dependent Raman scattering measurements for large electron densities. We attribute the discrepancy in measuring $\zeta$ and the Fermi energy to the renormalized mass resulting from many-body electron-electron interactions.

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I. INTRODUCTION

Over the last couple of decades, two-dimensional electron gases (2DEGs) embedded in quantum wells have provided a unique means for understanding many-body exchange and correlation effects (of the Coulomb interaction). However, direct study of spin-polarized two-dimensional electron gases, important for the understanding of spin-physics, only began in the last decade. This is due in part to advances in growth techniques of dilute semi-magnetic quantum wells with high electron mobilities, especially those of II-VI materials which serve as ideal systems to study the spin-polarized case, and in part to applications in spintronics—the use of electron spin in semiconductor devices as opposed to electron charge.

In II-VI paramagnetic heterostructures, spin polarization of the 2DEG is achieved through the application of an external magnetic field. This produces a large Zeeman splitting, induced through exchange interaction between the conduction band electrons of the quantum well and the Mn²⁺ ions. This means that in small magnetic fields, spin quantization dominates over orbital quantization leading to a spin-polarized 2DEG rather than quantum Hall states as found in GaAs quantum wells. Further, for the same electron density $n_s$, the dimensionless coupling constant $r_s$, which describes the strength of many-body electron-electron interactions, defined as $1/(\alpha_B \sqrt{n_s})$, is large due to the small Bohr radius $a_B$ that these materials exhibit. Corrections due to exchange-correlations, therefore, become important and will inevitably renormalize the electron mass and the Zeeman splitting, and hence, affect the manner in which the spin polarization degree and the Fermi energy of an electron gas are determined by spectroscopy.

In this work, we present a quantitative comparative study of fundamental parameters—the Zeeman energies, the spin polarization degree, the electron density and the Fermi energy—of a spin-polarized 2DEG embedded in Cd₁₋ₓMnₓTe single quantum wells using resonant electronic Raman scattering and photoluminescence (PL) in both zero and applied magnetic fields in the Voigt configuration. We will demonstrate that our PL results show collective behavior, allowing us to extract the bare Zeeman energy instead of the renormalized one while Raman scattering measurements show both. Additionally, we will show that for the range of densities accessible by us ($r_s$ between 1.8 and 3), an understanding of the renormalization of mass due to exchange-correlation effects is needed to explain the difference we observe in our measurements for the spin polarization and the Fermi energy for large electron densities using both Raman scattering and PL.

PL is a widely used spectroscopic tool for probing inter-band electronic excitations. In a zero
magnetic field, PL corresponds to electrons excited by absorption of photons above the absorption edge of the 2DEG: an electron is excited into the conduction band and a hole is created in the valence band. The hole then relaxes to the top of the valence band where it becomes localized due to ionized impurities and potential fluctuations, while electrons thermalize with the Fermi sea. This is followed by a recombination of the conduction band electrons with the localized holes. Wave vector conservation is relaxed, allowing for recombination of all electrons with any finite wave vector. The result is a broad line-shape, the spectral width of which corresponds to the Fermi energy (neglecting Coulomb interaction of the recombining electron and hole). In an applied magnetic field, both electron and hole bands split into two spin sub-bands, and recombination processes occur between these bands (see section IV.B.2).

Raman scattering is also a well-established tool for studying low energy intra-band elementary excitations of electron gases embedded in semiconductors. In the polarized configuration, in which the incoming and the outgoing light have the same polarization, Raman scattering probes charge-density fluctuations (plasmons) and single-particle excitations of an electron gas. In the depolarized configuration, in which the incoming and outgoing light polarization are orthogonal to each other, it probes, in zero applied magnetic field, spin-density excitations and single-particle excitations and in an applied magnetic field, it also probes spin-flip excitations.

This paper is arranged as follows. We describe and define the various excitations of a spin polarized two-dimensional electron gas, the bare and the renormalized Zeeman splitting energies, and the spin polarization in sections II.A and II.B. In section II.C we compare a few methods for obtaining the Fermi energy and the carrier density. The samples and experimental setup are presented in section III. Experimental results are given in section IV for both Raman scattering and PL measurements in two parts: section IV.A presents the zero magnetic field results for the determination of the Fermi energy and section IV.B presents the magnetic field dependent measurements for deducing the degree of spin polarization, the bare and renormalized Zeeman splitting, Z and Z*, respectively. We will discuss our results in-depth in section V, beginning with a comparison of the obtained Fermi energy values in section V.A; an interpretation of the PL lineshape and the Raman scattering results in terms of collective and single-particle behavior is given in section V.B, and in section V.C we end with a discussion of the spin polarization values obtained from PL and Raman scattering. Finally, we conclude in section VI.

II. SPIN-POLARIZED TWO-DIMENSIONAL ELECTRON GAS AND THE CARRIER DENSITY

A. Single-particle excitations and the Zeeman energies

Single-particle excitations (SPE) correspond to the kinetic energy change due to the transfer of wave vector to an electron gas by an exciting light source. To access the true excitation spectrum of single electrons across the Fermi disk, Raman scattering in the polarized configuration is used since screening mechanisms due to plasmons are killed under strong resonance conditions. Thus, in a zero magnetic field, the dependence of the SPE spectra on the in-plane wave vector gives the Fermi velocity. From the Fermi velocity and independent knowledge of the effective mass, the electron density and the Fermi energy can be deduced for an electron gas (see section IV.A).

In an applied magnetic field and for zero wave vector transferred to the electron gas, the energy of the collective spin-flip excitation, corresponding to all electrons simultaneously flipping their spin from spin-down to spin-up and vice versa, has been shown to follow Larmor’s theorem and to equal the bare Zeeman energy Z* [see insert (a) of Fig. 3]. In the presence of electron-electron interactions, the energy of the single electron spin-flip excitation, corresponding to a single electron flipping its spin, is shifted from Z by a local exchange-correlation field and leads to a renormalized Zeeman energy Z* [see insert (b) of Fig. 3].

B. Spin polarization

The degree of spin polarization of an electron gas is defined as

\[ \zeta = (n_1 - n_\downarrow)/(n_1 + n_\downarrow) = (k_{F\uparrow}^2 - k_{F\downarrow}^2)/(k_{F\uparrow}^2 + k_{F\downarrow}^2), \]

where \( n_\uparrow \) (\( n_\downarrow \)) is the density of spin-up (spin-down) electrons, and \( k_{F\uparrow} \) (\( k_{F\downarrow} \)) is the Fermi wave vector for the spin-up (spin-down) electrons. Assuming the same effective mass for the spin-up and spin-down subbands, which are split by \( Z^* \) [refer to the inserts of Fig. 3], \( \zeta \) can also be expressed as:

\[ \zeta = -Z^*/2E_F(0), \]

where \( E_F(0) = \hbar^2 \pi n_*/m^* \), \( m^* \) is the effective mass] is the Fermi energy in zero magnetic field.

A few groups have considered the spin polarization degree of 2DEGs in quantum wells. For example, in a previous study, Lemaître and co-authors pointed out the full spin polarization state of electrons embedded in Cd_{0.02}Mn_{0.08}Te quantum wells using magneto-absorption studies in the Faraday geometry. Independently, Astakhov et al. also deduced the spin polarization degree from the oscillator strength of charged
excitons in CdMnTe quantum wells using magneto-reflectivity measurements. In the first case, the spin-polarized physics is dominated by Landau quantization effects in the Faraday configuration. In the second case, low electron densities were considered with trion and exciton states dominating. For a degenerate electron gas out of Landau quantization, it is important to find alternative means of obtaining the Coulomb modified spin polarization. We will show that this possibility is afforded by both Raman scattering and PL.

C. Density and Fermi energy measurements

Carrier density, and essentially the Fermi energy by the definition above, in modulation-doped quantum wells have been measured by several means in the past. We discuss a few of these methods as follows. For low (<10^10 cm^-2) to very low electron densities (<10^9 cm^-2), optical detection of (dimensional) magneto-plasma resonances was used to determine electron densities in III-V quantum wells, and for high mobility carriers and concentrations, magneto-transport methods have been used for III-V materials. However, due to low mobility carriers in II-VI systems as compared to III-V systems, it is difficult to measure the carrier density by these means since the cyclotron frequency is smaller than the inverse of the relaxation time to be observed by far-infrared or microwave spectroscopy. We note that although our samples have high carrier mobilities and concentrations, the presence of Mn impurities renders transport measurements difficult. For such systems, carrier concentrations have been determined by other means: for example, by measuring the Moss-Burstein shift, in which the difference between the PL maximum and the absorption peak is determined by filling factors of Landau levels and through magneto-reflectivity spectra of charged excitons.

An additional way of extracting carrier concentration, which has worked for II-VI and III-V systems, is the measurement of the PL linewidth, however, due to disorder effects and wave vector break down, this method can sometimes provide inaccurate information (as we will show later in section IV. A. 2). An adequate fitting model is necessary to determine the density from the PL lineshape. Another method for extracting carrier densities in quantum wells is dispersive Raman scattering of intra-subband plasmons which has been demonstrated for both III-V systems as well as II-VI systems. Dispersive Raman scattering by plasmons, while shown to provide an excellent estimation of the electron density, also suffers from drawbacks. The observation of the plasmon mode in certain materials is limited by disorder and it becomes difficult to access by Raman scattering. In this paper, we will focus on the determination of the electron density and the Fermi energy from an analysis of the PL lineshape and by Raman scattering of single-particle excitations. With the exception of a few reports, the above means of measuring the density (the Fermi energy) have not considered the influence of the mass renormalization due to many-electron interaction, which will we show is important.

III. SAMPLES AND EXPERIMENTAL SETUP

Raman scattering and PL measurements were carried out on several samples with differing Mn^{2+} concentration and electron density. The structures were grown by molecular beam epitaxy on GaAs substrates. The Mn^{2+} concentration ranged from 0.46 % to 1.1 % and was determined from Raman scattering measurements (see section IV. B.1). As a representative, one sample that we will constantly refer to for our comparative study, sample B, had a 15 nm thick Cd_{1-x}Mn_xTe quantum well with Mn^{2+} concentration of x = 0.75%. The barriers of our quantum wells were made of Cd_{1-y}Mg_yTe with y = 15 % Mg. Modulation doping was achieved by introducing iodine within the Cd_{1-y}Mg_yTe top barrier with a spacer thickness of 40 nm. Our samples were immersed in superfuid helium (~1.5 K). A tunable Ti-sapphire laser (pumped by an Ar+ laser), with power densities below 0.1 W/cm² to avoid heating the Mn^{2+} ions, was used as exciting laser source. The laser was tuned to resonate close to the transitions between the first conduction band and the first heavy-hole band of the quantum well (E_l H_1 absorption edge) at ≈ 1.62 eV. For magnetic field dependent studies, our samples were mounted in the center of a 4.5 T superconducting solenoid producing a magnetic field in the plane of (Voigt configuration) and perpendicular to (Faraday configuration) the quantum well. Raman scattering measurements were carried out in the back-scattering geometry.

IV. EXPERIMENTAL RESULTS

A. Zero magnetic field

In this section, we will determine the Fermi energy and the electron density of our 2DEG systems using both Raman scattering and PL. We will begin with the determination of the Fermi velocity and then the Fermi energy E_F, Raman(0) by dispersive Raman scattering of SPEs. Later, we present results on the PL lineshape and deduce the Fermi energy E_F, PL(0).

1. Fermi velocity determination from Raman scattering by SPEs

Fig. 1(a) shows Raman scattering spectra by SPEs in the polarized configuration, at various in-plane wave vectors for sample B. For a given wave vector q, the intensity of the SPE line extends from zero to a maximum with peak at \(h v_F q\), where \(v_F\) is the Fermi velocity. The
In the second approach for obtaining \( v_F \), we use the Lindhard dielectric response function, including a broadening parameter (\( \sim 0.12 \text{ meV} \)) to phenomenologically account for the finite lifetime of the electron states and numerically integrating over the Fermi disk as outlined in Refs. 13 and 11. We again use \( m_b \) in our fit. Note that the values deduced from the Lindhard fits [shown in Fig. 1(a)] as solid lines] serve as checks for the values obtained from the SPE peak position. In Fig. 1(a), we describe the background upon which the SPE line rides, associated with the upper tail of the luminescence, as an exponential function, increasing towards lower absolute outgoing photon energies. This background was then added to the Lindhard function to enable a fit to our data, shown in the figure. From each fit, a value for \( v_F \) was determined and an average was taken over the range of wave vectors explored. \( E_{F, \text{Raman}}(0) \) and \( n_s \) were then obtained using Eq. (3). These values, from the Lindhard fit, are given in Table I for all samples studied. In the case of sample B, from the Lindhard fit, \( n_s \) and \( E_{F, \text{Raman}}(0) \) were found to be \( 2.9 \times 10^{11} \text{ cm}^{-2} \) and 6.5 meV, respectively.

The values determined from the SPE peak position, for the same sample, for \( n_s \) and \( E_{F, \text{Raman}}(0) \) were \( 2.7 \times 10^{11} \text{ cm}^{-2} \) and 6.2 meV, respectively, such that there is a good agreement between the two methods. The peak position coincides with the maximum of the Lindhard dielectric response function and hence the good agreement with the line fitting is as expected for all samples, except sample E: \( E_{F, \text{Raman}}(0) \) obtained from the Lindhard fit was 6.1 meV while that obtained from the peak position was 5.5 meV (see section V.A for further discussion and comparison with the Fermi energy value determined from the PL lineshape).

### 2. Fermi energy determination from the photoluminescence lineshape

We now consider extracting \( E_{F, \text{PL}}(0) \) from the PL lineshapes shown in Fig. 2(a). The PL lineshape shows a characteristic peak or maximum, which without disorder is associated with the energy gap recombination. The intensity decreases gradually with increasing photon energy to form a shoulder and then an edge positioned at the energy gap plus the Fermi energy. By naively taking the difference between the PL maximum and the PL edge, as illustrated in Fig. 2(a) for sample B, one obtains Fermi energy values that are less than those predicted by the Raman scattering measurements. These values are given in Table I and labeled \( E_{F, \text{PL peak}}(0) \). For example, for sample C, we obtained \( E_{F, \text{PL peak}}(0) = 3.5 \text{ meV} \) as compared to \( E_{F, \text{Raman}}(0) = 4.8 \text{ meV} \). The large error in estimating the Fermi energy is due to the precise determination of the fundamental band gap from the PL spectra. Broadening due to disorder causes the energy gap to be different (shift to lower energy) from the PL maximum; therefore, an adequate model is needed to extract \( E_{F, \text{PL}}(0) \) from the PL lineshapes.\(^{34,41,42}\) We perform such a PL lineshape fitting analysis using a phenomenological model described below.

Christen and Bimberg\(^{34}\) reported a detailed calculation on PL profiles of quantum wells by considering, separately, free-electron, free-hole and excitonic recombination processes, and by accounting for broadening effects due to thermal distribution of carriers and interface roughness or composition fluctuations and final state recombination processes. In addition, the authors considered both wave vector conservation and non-conservation. In the same spirit, we present a phenomenological model that describes the PL lineshape of our 2DEG systems. We assume a parabolic band throughout this paper, neglect lifetime broadening due to final state recombination processes, and assume an infinite heavy-hole mass (so that the valence band is flat with respect to the conduction band), as the holes are localized. Note that for the electron densities considered...
FIG. 2: (a) (Color online) Normalized PL spectra for several chosen samples with different Mn$^{2+}$ concentration and electron densities. The Fermi energy values are extracted from the PL lineshape as explained in the text. The PL lineshape for sample B shows an approximate measure of the Fermi energy value (vertical dotted lines) given as $E_{F, \text{PL peak}}(0)$ in Table I and the PL lineshape fitting (blue dash line). (b) Schematics of the conduction band (CB) and valence band (VB) used in our fitting model given in Eq. 4. A sample PL spectra is shown, depicting contributions to the various components in the expression (see text).

TABLE I: Sample Parameters. Values of $v_{F, \text{Raman}}$, $n_s$ and $E_{F, \text{Raman}}(0)$ were determined from the Lindhard lineshape fits, as described in section IV.A.1. Determination of $E_{F, \text{PL}}(0)$ is described in section IV.A.2. The manganese concentration is determined from the Raman measurements, described in IV.B.

| Sample | $n_s$ ($\times 10^{11} \text{cm}^{-2}$) | $x_{\text{Mn}}$ (%) | $v_{F, \text{Raman}}$ ($\times 10^6 \text{cm/s}$) | $E_{F, \text{Raman}}(0)$ (meV) | $E_{F, \text{PL peak}}(0)$ (meV) | $E_{F, \text{PL}}(0)$ (meV) |
|--------|---------------------------------|---------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|
| F      | 1.6                             | 0.82                | 11.1                        | 3.6                           | 3.0                           | 4.2                           |
| H      | 1.9                             | 0.96                | 12.1                        | 4.4                           | 3.6                           | 4.6                           |
| C      | 2.1                             | 0.79                | 12.7                        | 4.8                           | 3.5                           | 4.6                           |
| I      | 2.2                             | 0.96                | 13.0                        | 5.0                           | 3.3                           | 4.6                           |
| D      | 2.3                             | 0.78                | 13.3                        | 5.3                           | 4.1                           | 5.3                           |
| G      | 2.3                             | 0.84                | 13.4                        | 5.4                           | 4.3                           | 5.4                           |
| J$^a$  | -                               | 1.10                | -                           | -                             | 2.8                           | 4.2                           |
| E      | 2.7                             | 0.81                | 14.3                        | 6.1                           | 3.8                           | 5.2                           |
| B      | 2.9                             | 0.75                | 14.9                        | 6.5                           | 7.2                           | 8.5                           |
| A      | 3.0                             | 0.46                | 15.1                        | 6.8                           | 7.0                           | 8.2                           |

$^a$ $v_F$ could not be obtained from Raman scattering.

in this paper, Coulomb interaction between the Fermi disk and the hole state, known to affect the PL lineshape for very low electron densities, has been shown to be inhibited by screening and phase space filling; thus, the PL spectrum reproduces single-particle occupancy of the density of states. We can, therefore, disregard excitonic effects in the PL lineshape. We treat separately potential and energy fluctuations due to disorder effects and assume that the Fermi energy is constant. For nonconservation of wave vector, an analogous form of equation 18(b) of Ref. 34 for our PL lineshape is:

$$I(E) = Af(E - E_F - E_g) \int_0^{\infty} dx e^{(x - E_g)^2/(2\gamma^2)} \Theta(E - x)e^{(E - x)/(E_{\text{F}} - E_g)}. \quad (4)$$

Going from left to right of Eq. 4, $A$ is a proportionality constant and $f(E - E_F - E_g)$ is the Fermi distribution
function, where $E_g$ is the average energy gap, $E_F$ is the Fermi energy and $E$ is the photon energy. The Gaussian envelope function with $\gamma$ accounts for broadening due to disorder effects on the low energy side of the PL spectrum, and it corresponds to the width of the fluctuations in energy of the hole band due to disorder. The hole state, because of its heavy mass, is readily sensitive to electrostatic potential fluctuations caused by disorder effects resulting in hole localization. Since the electron mass is smaller than the hole mass and screening effects dominate in the electron plane, we assume zero potential fluctuation for electrons. The integral parameter $x$ is the local energy gap, the modified gap as a result of wave vector nonconservation and it relates to localization of the hole band in $k$-space due to in-plane potential fluctuations. These contributions are depicted in Fig. 2(b).

The adjustable parameters used in fitting our data [shown in Fig. 2(a)] in Eq. (1) are $A$, $\gamma$, $E_g$, $E_\delta$ and $E_F$. We emphasize that the influence of these parameters on the lineshape fitting model is well separated so that each parameter is uniquely determined. We have used $T_h = T_r = T = 1.5$ K, the experimental temperature. A sample fit is displayed in Fig. 2(a) as blue dash line for sample B. The discrepancy between the fit and experiment at the Fermi edge results from the presence of a Fermi edge singularity. The values obtained for $E_{F, PL(0)}$ are given in Table I for all samples. The values for $E_\delta$, $E_0$ and $\gamma$ range from $\sim 2$ to $\sim 5$ meV, 1602 to 1617 meV and $\sim 0.7$ to $\sim 1.2$ meV, respectively. For such a simplified fitting model, we find that $E_{F, PL(0)}$ and $E_{F, Raman(0)}$ are identical except for samples A, B, and E. For sample B, $E_{F, PL(0)} = 8.3$ meV, much larger than $E_{F, Raman(0)} = 6.5$ meV. We will discuss the results further in section IV.A. Next, we analyze the PL lineshape.

### Further analysis of the PL lineshape

We comment on additional features of the PL lineshape. First note that, in Fig. 2(a), the energy gap (near the PL maximum) increases in energy with increasing Mn$^{2+}$ concentration, going from sample A to sample J. The fitted values evolve from 1602 to 1617 meV. The dependence of the energy gap on Mn$^{2+}$ concentration has been reported by Matsuda et al.\textsuperscript{[18]} on CdMnTe systems and independently by Kossut et al.\textsuperscript{[19]}

Secondly, the PL lineshape gradually changes from sample A (large density) to sample J (low density), showing a gradual smearing of the shoulder near the Fermi-edge. Similar observations were made on Cd$_{1-z}$Mn$_z$Te quantum wells, for example, in Ref.\textsuperscript{[18]} and in Ref.\textsuperscript{[15]}. The behavior was qualitatively attributed to potential fluctuations which causes non-vertical recombination between conduction electrons and photo-generated holes. Depending on the amplitude of the potential fluctuation, related to $E_\delta$ in our model, the PL line peaks at the zone center (as is the case for sample A) or extends to the PL edge (as is the case for sample J).\textsuperscript{[15,18]} This effect increases with decreasing electron density as observed from sample A to J due to increasing sensitivity of electrons to the potential fluctuation. We therefore fit the PL lineshape considering potential fluctuations in the electron plane. For sample A, we obtained $E_\delta \sim 2$ meV and for sample J, we obtained $E_\delta \sim 5$ meV.

### B. Magnetic field effects

We now present the magnetic field dependent results. As in the last section, we will start with Raman scattering measurements and later present the magneto-PL results.

#### 1. Zeeman energies from Raman scattering

Under a small magnetic field, the lowest conduction subband splits into two spin bands as shown in the inserts of Fig. 3. In the depolarized configuration, the SPE spectrum consists of excitations from the majority (electrons having spin-down with density $n_1$) to the minority spin subbands (electrons having spin-up with density $n_1$). The spin-flip Raman spectra in Fig. 3 show two features below 6 meV: at $q = 0$, these lines are attributed to the collective spin-flip excitation, insert (a), and the single-particle spin-flip excitation, insert (b), corresponding to the bare Zeeman splitting $Z$ and the renormalized Zeeman splitting $Z^*$, respectively.\textsuperscript{[22,24]} The energy value of $Z^*$ is greater than $Z$ because of the renormalization of the spin subband separation due to exchange-correlation interactions.\textsuperscript{[22,25]} With a knowledge of $Z^*$ and the Fermi energy obtained in section IV.A, the degree of spin-polarization in our quantum wells can be determined. Also, knowing $Z$, the Mn$^{2+}$ content of our quantum wells can be obtained. We shall discuss the spin polarization values deduced from Raman scattering in section V.C.

In Fig. 4, we show the extraction of the Mn$^{2+}$ concentration for sample B using the modified Brillouin function. The Brillouin function describes the thermodynamic average of the spin state of Mn$^{2+}$ ions and is related to $Z$ by $Z = -N_0 \alpha x \langle S_z(B, T) \rangle$, where $\alpha$ is the exchange integral, $N_0$ is the number of unit cells per unit volume, $\langle S_z(B, T) \rangle = S_B \langle B \rangle / (k_B T)^{1/2}$ is the Brillouin function, $x$ is the mole fraction of Mn$^{2+}$, the spin value is $\sim 5/2$ for our Mn$^{2+}$ concentration, $\mu_B$ is the Bohr magneton, $g = 2$, and $S_B$ and $T_0$ are parameters associated with the manganese atoms.\textsuperscript{[2]} The magnetic field de-
a saturation magnetic field of 4 T, the Mn curve is a Brillouin function fitted to the data points. At

FIG. 4: Z values (spheres) obtained from Fig. 3 and plotted as a function of the magnetic field for sample B. The black curve is a Brillouin function fitted to the data points. At a saturation magnetic field of 4 T, the Mn$^{2+}$ concentration extracted = 0.75%, $Z = 3.5$ meV and the temperature $T_m = 1.5$ K.

dependence of $Z$ is well reproduced by the Brillouin curve (shown as a solid line) in the figure; this fit gives a Mn$^{2+}$ concentration of 0.75% and a temperature of 1.5 K for sample B. The manganese concentrations determined in this way are given in Table I for all samples.

2. Zeeman splitting from magneto-PL

In an applied magnetic field, electron and hole bands split; however, in the Voigt configuration, Zeeman splitting within the heavy-hole band is vanishingly small in small magnetic fields due to the hole spin alignment in the growth direction. Fig. 4 shows magneto-PL spectra on sample B in the Voigt configuration. Significant components of Fig. 4 at high magnetic field, are features associated with each spin population: Fig. 4(a), the majority spin-split subband for the spin-down electrons and, Fig. 4(b), the minority spin-split subband for the spin-up electrons. We access these spin subbands by changing the polarization of the detected photons. To access the spin-down population, the outgoing laser beam polarization ($E_s$) is orthogonal to the applied magnetic field ($B$). This is the $\sigma$ polarization shown in Fig. 4(a) for various magnetic fields. For the spin-down population, the outgoing polarization is parallel to the applied magnetic field, shown in Fig. 4(b). The latter is the $\pi$ polarization. The schematic diagram shown in Fig. 4(c) is a depiction of the spin subbands and the electronic transitions corresponding to the spectra shown in Fig. 4(a) and (b). The edges of the PL are labeled $\sigma_{\text{edge}}$ and $\pi_{\text{edge}}$.

For an understanding of Fig. 4 consider recombination processes occurring between the first heavy-hole band and the electrons. The valence band state for the heavy-hole can be expressed in terms of four component states,

$$|hh\rangle = \sum_j \alpha_j |J\rangle,$$

where $J = \pm \frac{1}{2}$, $\pm \frac{3}{2}$, and $|\alpha_j|^2$ are the probability amplitudes of the hole states relating to the transition amplitude and normalizing factors of the electron-hole recombination processes, calculated using the envelope function approximation and plotted in Fig. 4. In Fig. 4 the quantization axis is chosen along the $x$-direction and the growth direction is in the $z$-direction. At high magnetic fields, the heavy-hole state aligns parallel to the field since the best quantization is along the field direction. The heavy-hole wave function is then described by $|hh\rangle \simeq \alpha_{-\frac{1}{2}} |-\frac{1}{2}\rangle + \alpha_{\frac{3}{2}} |+\frac{3}{2}\rangle$, where $\alpha_{-\frac{1}{2}}$ and $\alpha_{\frac{3}{2}}$ are shown in Fig. 4. Using well-known electric dipole transition selection rules for $\sigma$ and $\pi$ photons,

$$\langle J' | P_\sigma | J \rangle = 2p \delta_{J,-J'},$$
$$\langle J' | P_\pi | J \rangle = p(\delta_{J,-J'} + \sqrt{3}\delta_{J,-3J'}).$$

FIG. 3: Raman scattering measurements on sample B for various in-plane magnetic fields (Voigt configuration). Two lines corresponding to the collective and individual spin-flip excitations associated with the bare Zeeman splitting $Z$ and the renormalized Zeeman splitting $Z^*$, respectively, are shown, in accordance with Larmor’s theorem at zero wave vector. The inserts (a) and (b) show the spin-splitting of the conduction band with two spin populations: spin-up $n_1$ and spin-down $n_1$. Insert (a) shows the collective spin-flip of electrons from the spin-down subband to the spin-up subband, and insert (b) shows a single electron flipping its spin from spin-down to spin-up subband. The corresponding separation between the spin subbands yields $Z^*$.
where $p$ is a constant and $J' = \pm \frac{1}{2}$, we expect to see the following recombination processes (electrons to holes): $\sigma_0 (|\frac{1}{2}\rangle \Rightarrow |\frac{1}{2}\rangle)$; $\sigma_0 (|\frac{1}{2}\rangle \Rightarrow |\frac{1}{2}\rangle)$; $\sigma_0 (|\frac{1}{2}\rangle \Rightarrow |\frac{1}{2}\rangle)$ and $\sigma_1 (|\frac{1}{2}\rangle \Rightarrow |\frac{1}{2}\rangle)$. The luminescence line is dominated by $\sigma_0$ and $\sigma_0$ recombination processes at high and low magnetic fields. $\sigma_1$ has a lower contribution than $\sigma_0$ according to our calculations shown in Fig. 6. For intermediate magnetic fields, contributions from $\alpha_{\frac{1}{2}}$ and $\alpha_{\frac{1}{2}}$ increase and we expect to have additional processes $\pi_1 = |\frac{1}{2}\rangle \Rightarrow |\frac{1}{2}\rangle$ occurring and a reinforcement of $\sigma_1 = |\frac{1}{2}\rangle \Rightarrow |\frac{1}{2}\rangle$ occurring. The $\sigma_1$ and $\pi_1$ transitions are mirror images of the $\pi_0$ and $\sigma_0$ transitions, respectively, arising from the fact that the hole spin state is impure. These processes are in very good agreement with our data shown in Figs. 5(a) and Fig. 5(b).

The transition energies extracted from Fig. 5(a) and (b) are plotted in Fig. 5(d) as a function of the bare Zeeman energy obtained from Raman scattering (from Fig. 4). Note that the PL edges in both $\sigma$ and $\pi$ polarizations and the values for $\sigma_1 (\pi_1)$ and $\pi_0 (\sigma_0)$ nearly overlap, showing good agreement. The separation between the spin-up and the spin-down subbands is equivalent to the Zeeman energy as depicted in Fig. 5(c). The difference between the transition $\pi_0$ and $\sigma_0$ is expected to equal $Z^*$ (for an interacting electron gas). In Fig. 5(d), however, the energy separation between the peak position $\sigma_0$ and the peak position $\pi_0$, is equivalent to $Z$ and not $Z^*$ contrary to our expectation.

To check the consistency of our observation for the Zeeman energy, measurements were taken in the Faraday geometry on sample B and this is shown in Fig. 7(a). In the Faraday configuration, the magnetic field is parallel to the growth axes and photoluminescence from the heavy-hole and light hole-bands are known to split symmetrically into two circularly polarized components, $\sigma^+$ and $\sigma^-$ components. In Fig. 7(a), these spectra, unlike the Voigt spectra, are mixed with Landau oscillations. The characteristic separation between the $\sigma^+$ and the $\sigma^-$ photoluminescence is equivalent to the heavy-hole splitting energy of 15.7 meV at 4 T, Fig. 7(b). From experimentally determined values for the valence band exchange integral ($N_0\alpha = 0.22$ eV) and that for the conduction band exchange integral ($N_0\beta = -0.88$ eV = $4N_0\alpha$),

FIG. 5: PL spectra in the Voigt configuration on sample B at various magnetic fields and 1.5 K: (a) spectra from the majority spin-split subband taken with the in-plane magnetic field perpendicular to the polarization of the outgoing emission; (b) spectra from the minority spin-split subbands taken with the in-plane magnetic field parallel to the outgoing emission. (c) Schematic diagram showing the electronic transitions. d) Points extracted from (a) and (b) for the following transitions: $\sigma_1$, $\sigma_0$, $\pi_1$, $\sigma_{\text{edge}}$ and $\pi_{\text{edge}}$ depicted in (c). The $\pi_1 (\sigma_1)$ transitions are identical to the $\sigma_0$ ($\pi_0$) transitions. The difference between the $\pi_0$ and the $\sigma_0$ transitions gives $Z_{\text{PL}}$, refer to Fig. 5.
the heavy-hole splitting is equivalent to five times the conduction band splitting and therefore is expected to equal $5Z^*$. However, the Zeeman energy value obtained from Fig. 7(b) is identical to $Z$, as was the case in the Voigt configuration. We will discuss the implication of this observation in section V.A and compare our measured values to the Raman scattering results.

FIG. 6: (Color online) Decomposition of heavy-hole states in an applied magnetic field for sample B calculated for the Voigt configuration and a temperature $T = 1.5$ K. Each curve represents the probability amplitude of heavy-hole states in our quantum wells.

FIG. 7: Magneto-PL measurements on sample B in the Faraday configuration. (a) Spectra taken at various magnetic fields at 1.5 K. (b) Transition energies extracted from (a).

FIG. 8: Ratio of Fermi energy values obtained from Raman scattering and the PL lineshape fitting as a function of the Fermi velocity from Raman scattering. The vertical error bars are estimated from both PL and Raman scattering. The two results are identical for most samples except for samples A, B and E. The dash line in the figure shows identical results for both Raman scattering and PL.

V. DISCUSSION

A. The Fermi energy values

To investigate the Fermi energy values obtained from the PL and Raman scattering measurements, we plot in Fig. 8 the ratio $E_{F, \text{PL}}(0)$ to $E_{F, \text{Raman}}(0)$ as a function of $v_F^2$ obtained from Raman scattering (refer to Table I). Recall that in section IV.A, the Fermi energy values are the same for most of our samples except for samples A, B, and E. The uncertainties in measuring the ratio of Fermi energies (by the Lindhard and the PL lineshape fitting analysis) are shown in Fig. 8 as vertical error bars. The error is larger at low and large densities. Dispersive Raman scattering measurements are limited by disorder and for low electron densities ($< 1.5 \times 10^{11}$ cm$^{-2}$), the SPE Raman line cannot be discernible since it gets too close to the excitation line and this will also affect the lineshape fitting. Although the PL lineshape fitting could not perfectly fit the high density samples near the Fermi edge, we can determine the Fermi energy with an error of less than 5%.

For samples A and B, the $E_{F, \text{Raman}}(0)$ values are smaller than those obtained from the PL lineshape while for sample E, the $E_{F, \text{Raman}}(0)$ value is larger. For sample E, due to large disorder evident in the PL lineshape (with $E_0 \sim 4$ meV, and this is also the case for samples J), the SPE line was difficult to fit by the Lindhard model. The peak position values from Raman scattering however gave an $E_{F, \text{Raman}}(0)$ value of 5.5 meV which agrees with $E_{F, \text{PL}}(0) = 5.2$ meV. For sample A and B, the estimated error in obtaining $E_{F, \text{PL}}(0)$ is less than the difference between the values for $E_{F, \text{Raman}}(0)$ and
$E_{F, PL}(0)$, we note that the measured densities from both Raman scattering and PL are large.

PL provides information on the entire curvature of the electron band. Hence, information on the renormalized Raman scattering and PL are large. This means that $E_{F, PL}(0)$ includes the mass correction and should provide an accurate estimation of the Fermi energy within the parabolic band approximation (assuming negligible contributions from Coulomb interaction between electrons and holes). The Raman scattering process probes a limited region of the electronic band close to the Fermi energy, meaning that Raman scattering measurements are accurate in the determination of $v_F$.

In Fig. 8 the ratio $E_{F, PL}(0)/E_{F, Raman}(0)$, assuming Eq. (3) for $E_{F, Raman}(0)$ and $E_{F, PL}(0) = (1/2)m^*v_F^2$, is equal to the ratio $m^*/m_b$. In Cd$_{1-x}$Mn$_x$Te quantum wells, the available information on the electron mass is that measured for CdTe by cyclotron resonance experiments, $m_b$. This mass does not include additional corrections due to many-body electron-electron interaction and gives only the bare mass. As we have assumed a value for this bare mass ($m_b = 0.105m_0$), the absolute values found for $m^*/m_b$ are unclear, but the qualitative behavior of $m^*/m_b$ with a minimum around $v_F = 13.4$ ($r_s = 2.3$) resembles calculations of Fig. 10 in Ref. 8. Nonetheless, we estimate less than 20% increase in mass.

Our results also reaffirm that extracting the Fermi energy from the PL maximum and the Fermi edge of quantum wells gives inaccurate results and that a good lineshape fitting analysis is essential. Further, if we correct the values for the densities in Table I, deduced from $v_F$ assuming a bare mass, with the mass renormalization found in Fig. 8 we find for sample B $n_s = 4.9x10^{11}$ cm$^{-2}$ instead of $2.9x10^{11}$ cm$^{-2}$.

B. Collective and single-particle behavior

We have shown in section IV.B1 that the Raman scattering measurements identify both collective and single-particle behavior of a spin-polarized 2DEG, whereas for the magneto-PL measurements given in section IV.B2, only the bare Zeeman splitting $Z$ was extracted. Values of $Z$ obtained from the PL lineshape in the Voigt and Faraday configurations, as well as $Z^*$ from Raman scattering are plotted in Fig. 9 as a function of $Z$ from Raman scattering. In that figure, the $Z$ values extracted from the PL measurements are consistent with the Raman scattering values. The analysis was repeated for the samples listed in Table I and the results were found to be consistent: that is, the PL lineshape gives only $Z$ and not $Z^*$. As $Z$ is associated with a spin-flip energy related to collective excitations, we might conclude that collective effects influence the PL behavior.

To understand the magneto-PL behavior, let us consider the various transition processes that occur. We follow the evolution of the PL profile, shown in Fig. 10.
lowing the work of Kossacki and co-authors for holes. This figure shows the representation of many-body states in a quantum well. In the initial state, shown in panel (1), a photon is absorbed by an electron creating a hole in the first heavy-hole spin split subband. In the final state, panel (2), a photon is emitted with two possibilities arising: a) an electron in the spin-up band recombines with the hole or b) an electron in the spin-down band recombines with the hole leaving an unfilled space in either spin-up or spin-down bands. The difference between the energies of the spin-up \((E_\uparrow)\) and spin-down \((E_\downarrow)\) transitions, which are shown experimentally in Fig. 3(b) for the \(\pi_0\) transition and Fig. 3(a) for the \(\sigma_0\) transition of section IV.B.2, is exactly the bare Zeeman splitting energy. This is possible, if, the final state in the transition \(E_\uparrow\) is an excited state of a \(q = 0\) spin-flip wave whose energy is \(Z\). Hence, the difference between the transitions for the spin-up and the spin-down subbands yield \(Z\) and not \(Z^*\). We therefore conclude that the PL spectra is insensitive to the exchange modified spin splitting \(Z^*\) but exhibit collective recombination processes. Additionally, we conclude that Raman scattering provides a better measure of both the Zeeman splitting \(Z\) and the modified Zeeman energy due to Coulomb interactions \(Z^*\).

C. Determination of the spin polarization degree from Raman scattering and PL

We now turn to the determination of the spin polarization degree \(\zeta\) from Raman scattering and PL. Consider the magneto-PL measurements in Fig. 4 of section IV.B.2. Assuming a two-dimensional parabolic band for each spin-split subband and the same mass renormalization for each, then from the PL lineshape, the density of spin-up electrons \(n_\uparrow \propto E_\uparrow\) and that for spin-down electrons \(n_\downarrow \propto E_\downarrow\) where \(E_\uparrow = E_{\text{edge}} - E_0 - \delta w\) and \(E_\downarrow = E_{\text{edge}} - E_0 - \delta w\) are the PL linewidths in the \(\sigma\) and the \(\pi\) polarizations, respectively. Here \(\delta w\) is broadening due to disorder effects on the low energy side of the magneto-PL spectra (see Fig. 5(a) and (b)). For an in-plane magnetic field, the hole orbit is not quantized, implying that the localization length is unchanged. This assumes that broadening due to disorder, localized in the hole band, is independent of the applied magnetic field while localization occurs in plane. Since the heavy-hole splitting is small in the Voigt configuration, we can assume the same disorder effect for both heavy-hole spin split bands. We therefore approximate the width contribution \(\delta w\) to \(\gamma\) (the energy fluctuation parameter for zero magnetic field disorder contribution to the PL width obtained in section IV.A).

From Eq. 1 in the introduction, \(\zeta\) can be rewritten as

\[
(\epsilon_l - E_l)/ (E_l + E_l).
\]

The values of \(\zeta\) obtained by this means, labeled \(\zeta_{\text{PL}}\), assume an equal mass renormalization for both spin population, independent of the spin polarization degree. This is certainly valid for intermediate spin polarization degrees. We compare in Fig. 11(a) for sample C and in Fig. 11(b) for sample B \(\zeta_{\text{PL}}\) values obtained from PL and Raman scattering for (a) sample C and (b) sample B. \(\zeta_{\text{Raman}}\) values are plotted in Fig. 11(a) for sample C, the PL values (as well as the Raman values) for the bare Zeeman energy \(Z\) from Raman scattering. We also define a spin polarization degree based on Raman scattering values as \(\zeta_{\text{Raman}} = -Z_{\text{Raman}}/ 2E_F\). Raman and \(\zeta_{\text{PL}}\) was obtained from the width of the PL in the \(\sigma\) and the \(\pi\) configuration (see Fig. 5). \(\zeta_{\text{Raman}}\) and \(\zeta_{\text{PL}}\) are the theoretical values for the interacting and bare spin polarization degrees, respectively. \(\zeta_{\text{Raman}}\) (orange dot-dash curve and black dotted line) are the corrected values obtained using the mass correction of Fig. 5.
well with the model. The good agreement validates the fact that the Fermi energy values obtained from Raman scattering and PL are identical for sample C. In the case of sample B in Fig. 11(b), the \( \zeta_{\text{PL}} \) values are lower than the Raman scattering values and all values (including the \( \zeta_{\text{Raman}} \) values) are in poor agreement with the model. We suspect the strong mass renormalization found in Fig. 8 for this sample (and sample A) to be at the origin of this inconsistency. Indeed, densities given in Table I are determined from \( v_F \), which does not take into account the mass renormalization found in Fig. 8. If we now correct all densities for the mass, hence the new density \( n_{2D} = (m^*/m_b)^2 \times n_s \), and recalculate the spin polarization degrees with the new densities, we find no change for sample C, but significant changes for sample B (shown as orange dot-dash line labeled \( \zeta_{\text{xc,new}} \) and black dotted line labeled \( \zeta_{\text{b,new}} \)), such that the results become consistent. Hence, the calculated renormalized spin polarization degree is now comparable with \( \zeta_{\text{PL}} \) and \( \zeta^* \).

We conclude that that \( \zeta_{\text{PL}} \) and \( \zeta^* \) are reliable estimations of the spin-polarization degree. Furthermore, our results suggest that the Fermi energy values obtained from the PL lineshape fitting analysis can be trusted. On the other hand, the Raman scattering determination of the Fermi energy and \( \zeta \) using the bare mass, has to be corrected for the mass renormalization.

Finally, we point out that in Fig. 11 and for the same manganese concentration, the spin polarization degree shows an inverse relationship with the electron density, when comparing Fig. 11(a) and Fig. 11(b) on the same vertical scale. This behavior is predicted rather well by the Raman scattering and PL results.

VI. CONCLUSIONS

We have performed a comparative study on a spin-polarized 2DEG using resonant electronic Raman scattering and PL. Three key observations were made after measuring the Fermi velocity, the Fermi energy, the Zeeman energies and the spin-polarization degree. First, assuming a parabolic band, the Fermi velocity and the Fermi energy measured from Raman scattering was comparable to that measured from the PL lineshape for moderate electron densities, whereas for large electron densities, the values differ unless a renormalized mass was introduced. Secondly, discrepancy in the spin polarization degree \( \zeta \) also occurs for the samples showing this difference in the Fermi energy value. The discrepancies are attributed to the mass renormalization, which we have defined as the ratio between the Fermi energies extracted from PL and that deduced from Raman scattering. We checked the consistency of this result by a comparison with an exact model of the spin polarization. A good agreement was obtained after the density, extracted from \( v_F \), was corrected for the mass renormalization. Our results suggest that the effective mass is modified in the presence of many-body electron-electron interaction for the range of \( r_s \) values studied, though this range is small.

Thirdly, the magneto-PL lineshape gives \( Z \) instead of \( Z^* \), contradictory to what we expect. Using a phenomenological analysis, we showed that the PL lineshape is insensitive to the exchange modified spin splitting \( Z^* \) but is influenced by collective effects.

From the above analysis, we conclude that Raman scattering determines \( v_F \) and directly measures the bare and the renormalized Zeeman splitting accurately while PL provides accurate determination of the Fermi energy and the bare Zeeman splitting energy. In addition, the PL lineshape gives a good estimate of the renormalized spin polarization for low spin polarized systems, while for the high spin polarized case, determination of the spin polarization degree requires knowledge of \( Z^* \) from Raman scattering and the Fermi energy from PL.

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The plasmon mode in our quantum wells needed too strong an illumination power to be excited, and coupled with the different resonance conditions with the SPEs, we therefore did not consider it.

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