

The Influence of Internal Interfaces on Charge-Carrier Diffusion in Semiconductor Heterostructures

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The ongoing miniaturization of semiconductor devices renders charge-carrier transport along interfaces increasingly important. The characteristic length scales in state-of-the-art semiconductor technology span only a few nanometers. Consequently, charge-carrier transport inevitably occurs directly at interfaces between adjacent layers rather than being confined to a single material. Herein, charge-carrier diffusion is systematically studied in prototypical active layer systems, namely, in type-I direct-gap quantum wells and in type-II heterostructures. The impact of internal interfaces is revealed in detail as charge-carrier diffusion takes place much closer to or even across the internal interfaces in type-II heterostructures. Type-I quantum wells and type-II heterostructures exhibit comparable diffusion rates given similar inhomogeneous exciton linewidths. Consequently, the changes in the structural quality of the interfaces are responsible for changes in diffusion and charge-carrier transport along interfaces rather than the existence of the interfaces themselves.

local excitation gradients around laser spots. Understanding the light-induced charge-carrier transport plays a critical role in improving modern technologies, as it affects the performance of many semiconductor devices. One example is the critical importance of the diffusion length for the efficiency in solar cells.^[9] Charge carriers that recombine before diffusing to the space charge layer do not contribute to current generation, which, in turn, results in a loss in efficiency.

The influence of internal interfaces on device performance becomes increasingly significant as optoelectronic devices continue to be miniaturized. Type-II semiconductor heterostructures provide ideal model systems for studying the effects of these interfaces. In our study, two adjacent quantum wells are separated by an extremely

thin intermittent barrier, such that the lowest energy state of the electrons in the conduction band is in one quantum well while that of the holes in the valence band is in the other quantum well. The wave function maximum of the electrons and holes is much closer to the internal interfaces in the type-II heterostructures compared to type-I quantum-well structures. In the latter, the wave function maximum is in the center of the quantum well when internal fields are absent. Consequently, charge-carrier transport should be significantly more affected by interfaces in type-II heterostructures. This is especially true for the transport of charge-transfer excitons (CTXs).^[10] Their wave functions, by definition, span across the internal interface. As a result, the carrier transport occurs directly within or along the interface.

Current studies are intensively investigating carrier diffusion in perovskites, quantum structures and monolayers.^[11–15] In the latter, in particular, charge-carrier transport also takes place directly at the interfaces and is presumably strongly influenced by them. However, so far, the explicit influence of the interface on charge-carrier transport has not been investigated.

In this study, we determine the density-dependent diffusion coefficient for a free electron–hole plasma in type-II heterostructures as well as the respective type-I quantum wells constituting them by time-resolved photoluminescence (TRPL) imaging spectroscopy and three-pulse four-wave mixing (FWM) spectroscopy. In addition, we use FWM spectroscopy to determine the diffusion coefficients of excitons in both sample types. This systematic approach allows us to uncover the impact of the internal interface on the diffusion of charge carriers and excitons while

1. Introduction

Semiconductors are the fundamental components of optoelectronic devices such as electronics, solar cells,^[1–3] light-emitting diodes,^[4,5] photodetectors, and lasers.^[6,7] The charge-carrier transport through these materials is presumably the vital factor for the success of such devices.^[8] Optical spectroscopy easily accesses these properties without the need for additional processing. For example, optically injected charge-carriers diffuse through the semiconducting materials without external bias due to the

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minimizing effects due to sample quality variations. We find that diffusion is much more related to the inhomogeneous linewidth of the exciton resonances in the samples than to the presence of an internal interface. Intriguingly, this should result in interfaces not being the limiting factor in miniaturized structures as long as the quality of the semiconductor layer is maintained despite the proximity to interfaces.

2. Sample Design

We study four multiple quantum-well heterostructures grown by metal–organic vapor-phase epitaxy. Two of the four samples are type-II heterostructures consisting of 50 repetitions of 7.7 nm thick

(Ga,In)As quantum wells followed by a 1 nm thick interlayer, 7.7 and 7.5 nm thick Ga(As,Sb) quantum wells with Sb concentration of 3.3% and 7.0%, respectively. The In concentration in both samples is about 5.8%. The other two samples consist of either 50 repetitions of (Ga,In)As quantum wells embedded in GaAs barriers or 10 repetitions of Ga(As,Sb) quantum wells embedded in GaAs barriers with a Sb concentration of 7%. While the latter two samples provide type-I quantum-well structures with spatially direct transitions, the type-II heterostructures allow a spatially indirect transition from one quantum well to the adjacent one. The band edges and the possible transitions of the different samples are shown in **Figure 1a**.

We identify the respective transition energies and exciton resonances from the linear absorption of the samples derived from transmission measurements shown in **Figure 1b**. The type-I

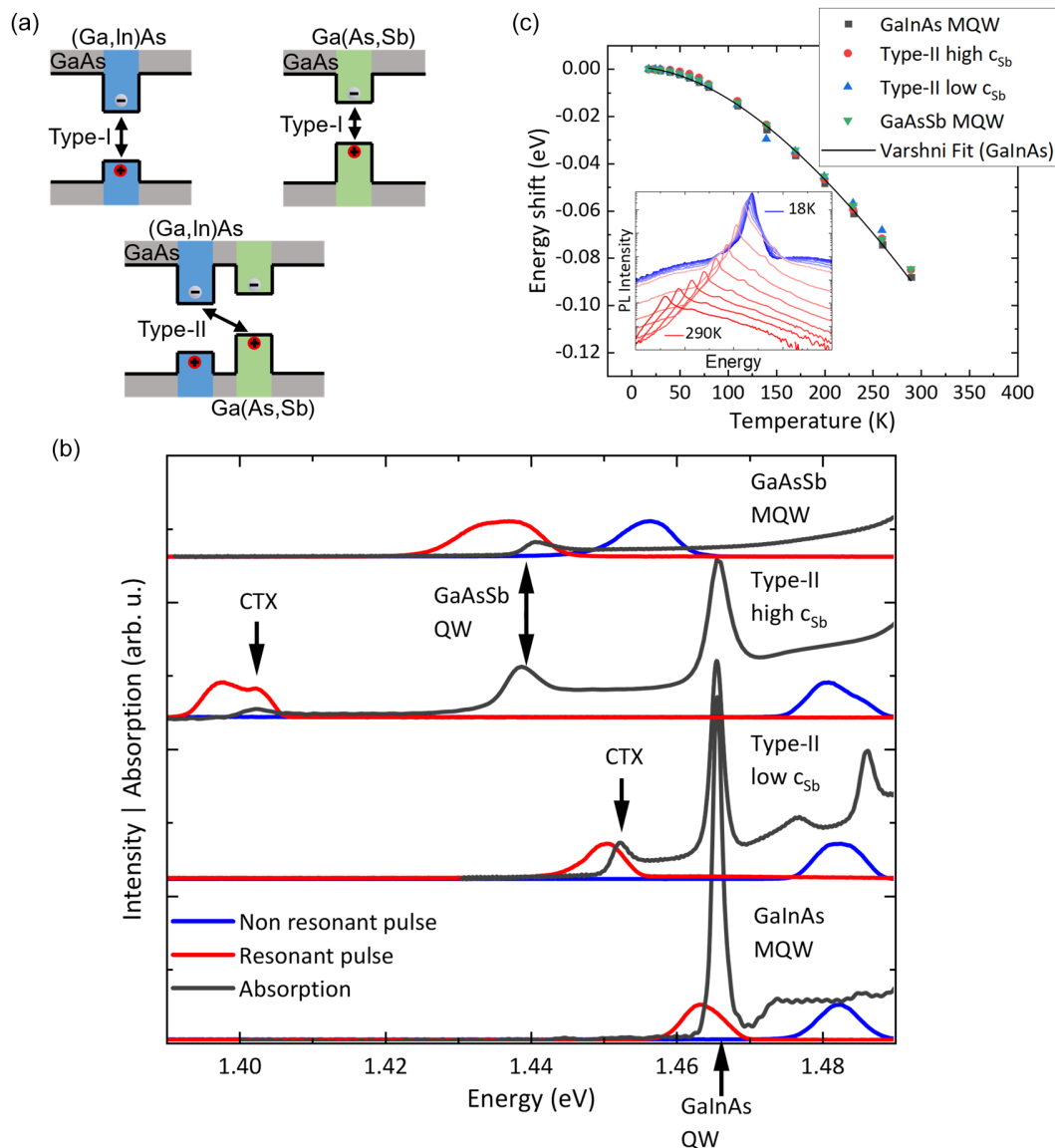


Figure 1. a) Schematic illustration of the band edge as function of growth direction in the type-I and the type-II heterostructures. The investigated type-I transitions are associated with the (Ga,In)As or the Ga(As,Sb) quantum wells while the type-II transitions occur between the Ga(As,Sb) and the (Ga,In)As quantum wells. b) Resonant and off-resonant excitation pulses used in the FWM experiments in addition to the sample absorption. c) Temperature-dependent energy shift of the PL maximum for all four samples. Representative temperature dependent PL spectra of the (Ga,In)As multi-quantum-well sample are given in the inset.

quantum-well structures each show one 1s exciton resonance at 1.440 and 1.465 eV in the Ga(As,Sb) and the (Ga,In)As quantum-well sample, respectively. The type-II heterostructure with the same Sb content also shows exciton resonances at these two energies, corresponding to the spatially direct transitions of the Ga(As,Sb) and the (Ga,In)As quantum wells. We attribute the additional exciton resonance at 1.402 eV to the CTX. The other type-II heterostructure with lower Sb content shows the exciton resonance of Ga(As,Sb) quantum wells at 1.485 eV and, correspondingly, the CTX resonance at 1.452 eV. The respective optical excitation pulses used for resonant excitation of the lowest energy excitons as well as the pulses used for nonresonant excitation of the free electron-hole plasma are also plotted for the specific samples in Figure 1b.

The measured temperature-dependent photoluminescence (PL) spectra for an excitation energy of 1.95 eV are given in Figure 1c. Traditionally, they are considered as a measure of the disorder in the sample and thus the sample quality.^[16] In our case, all samples show the same temperature dependence which follows a Varshni-like behavior without any indications of a disorder-induced S-shape. This confirms the high structural sample quality with negligible disorder and only few or very shallow localized states.

3. Experimental Section

The diffusion for resonant and nonresonant excitation is monitored by a three-pulse four-wave mixing experiment. We use the output of a 1 MHz repetition rate ultrafast laser amplifier operating at a center wavelength of 1030 nm to drive an optical parametric amplifier (OPA). The OPA generates approximately 50 fs pulses which are tunable across the relevant range from 800 to 900 nm. The pulses of the OPA are divided into two using a beam splitter. One part propagates over a linear delay stage and is then trimmed to the desired spectrum using appropriate dielectric short-pass and long-pass filters. This part is then split into two once more; the pulses are marked as pulse #1 and pulse #2 in Figure 2a. Both are focused on the sample under a relative angle α of 15.65° ensuring spatial and temporal overlap. To determine the spot size, we took a camera image at the optical focus and used the full width at half maximum in the horizontal and vertical directions to calculate the ellipsoid area. The resulting spot size is $3868 \pm 341 \mu\text{m}^2$. The interference pattern of both pulses creates a laser-induced density grating on the sample. The residual beam exiting the first beam splitter is labeled pulse #3. It is spectrally tailored to probe the desired exciton resonances of the samples and is subsequently focused on the sample overlapping the density grating. A second linear delay stage defines the time difference between the pulse pair #1–#2 and pulse #3. The latter diffracts by the density grating in the direction $\vec{k}_3 + (\vec{k}_2 - \vec{k}_1)$. The diffracted signal is detected by a photodiode (PD) and measured by lock-in technique. The optically generated density grating decays with time due to both diffusion and recombination of the charge carriers. Optical pump-optical probe spectroscopy is employed to determine the recombination. Using this data, the diffusion coefficient can be derived from the decay time of the diffracted signal intensity.

We corroborate our findings by data from TRPL spatial imaging as an independent approach to determine the diffusion of charge carriers.^[17,18]

Here, the excitation light source is an 80 fs Ti:Sa laser oscillator operating at a repetition rate of 78 MHz tuned to a central energy of 1.49 eV. A microscope objective focuses the beam onto the sample. A 1951 USAF resolution test chart imaged into the streak camera is used to calibrate the spatial resolution. The spot size of $6.5 \pm 0.5 \mu\text{m}^2$ is determined directly from the streak camera image. The horizontal pixels of the streak camera map the spatial distribution of the excitation across the sample. The diffusion is determined from the time dynamics of the spatial profile of the emission spot imaged to the streak camera. It displays the horizontal extension of the PL on its horizontal axis while the vertical axis represents the time axis. A typical spatially resolved image taken with the streak camera is shown on the left-hand side of Figure 3a. The diffusion becomes visible in the form of a spatial broadening by normalizing the detected light intensity for all time steps (Figure 3a, right). The samples are mounted in a liquid helium flow cryostat featuring cylindrical heat exchangers at a temperature of 6 K.

4. Results and Discussion

The diffusion becomes directly evident when plotting the FWM decay. Figure 2b gives exemplary data as function of the time delay between pulse #3 and the pulse pair #1–#2. For negative time delays, pulse #3 impinges on the sample first, that is, before the pulse pair #1–#2 injects the diffraction grating. Consequently, pulse #3 does not experience diffraction by a density grating and the signal intensity of the PD is very low. At time $t = 0$ ps, the pulse pair #1–#2 controls the lateral carrier distribution determined by the common beam cross-section of the two laser pulses. Pulse #3 diffracts most efficiently for times close to $t = 0$ ps when the density grating is at its maximum. Scattering between the carriers leads to a lateral expansion of the charge carriers within the quantum wells and, thus, to a degradation of the density grating. This is directly probed by the decreased diffraction efficiency of pulse #3 with increasing time delay.

We use exponential fits to extract the decay dynamics of the density grating (T_S) after nonresonant excitation (cf. Figure 2b). For resonant excitation, a coherent FWM process initially contributes but decays within the first picoseconds in addition to the incoherent FWM process driven by the population grating.^[19] This initial rapid decay of the coherent contribution is accounted for by a biexponential fit. Here, the fast decay of the biexponential fit characterizes the coherent regime, while the slower time constant (T_S) relates to the incoherent decay of the population grating due to diffusion.

In principle, the density grating also decays by recombination. However, the recombination in these samples is about an order of magnitude slower than the decay of the density grating by diffusion. We confirm this by optical transmission experiments (Figure 2b). The change of the optical transmission for the (Ga,In)As quantum-well sample yields the population lifetime T_1 , which we use to calculate the diffusion coefficient from the FWM data according to

$$D = \left(\frac{1}{T_S} - \frac{2}{T_1} \right) \times \frac{g^2}{8 \times \pi^2} \quad (1)$$

Here, the diffusion coefficient is denoted by D , while the decay time T_S is determined from the exponential fit to the FWM

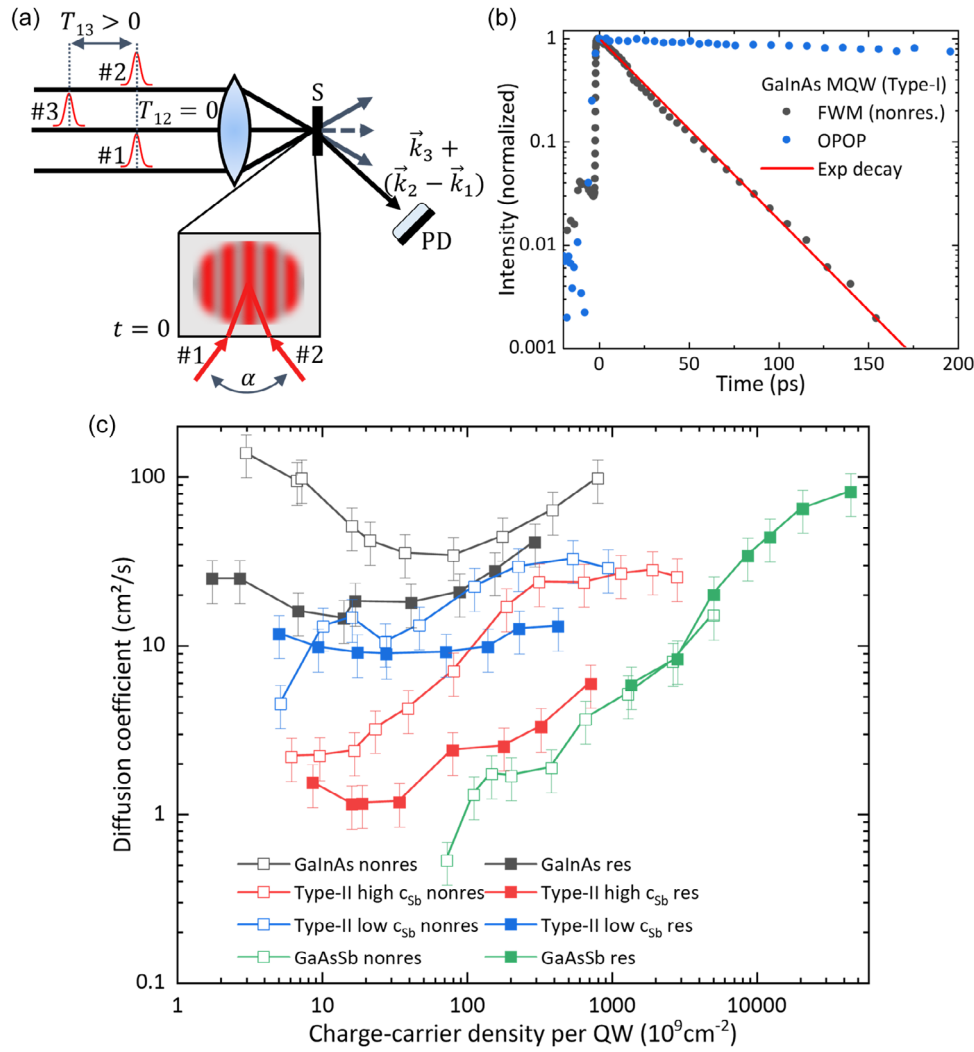


Figure 2. a) Illustration of the correlation between the three pulses in FWM. While pulses #1 and #2 reach the sample at the exact same time to induce the density grating, pulse #3 hits the sample after a temporal delay and may then be diffracted by the grating in the direction $\vec{k}_3 + (\vec{k}_2 - \vec{k}_1)$, where it is detected by a photodetector. b) FWM data after nonresonant excitation of the type-I (Ga,In)As sample at a charge-carrier density of $1.76 \times 10^{11} \text{ cm}^{-2}$. The black dots show the monoexponential decay, which is much faster than the decay of the population (blue dots) measured via optical-pump optical-probe spectroscopy under the same excitation conditions. c) Diffusion coefficients obtained by three-pulse FWM of the four samples for resonant and nonresonant excitation conditions.

decay. Additionally, g represents the lattice constant of the injected grating. We calculate an effective lattice constant of $3.103 \mu\text{m}$ for an excitation energy of 1.467 eV according to

$$g = \lambda / \left(2 \times \sin\left(\frac{\alpha}{2}\right) \right) \quad (2)$$

This approach yields the diffusion coefficient for all four samples, for resonant excitation of the lowest-energy exciton resonance and for nonresonant excitation of an electron–hole plasma.

We estimate the experimental uncertainty of D by assuming an error of 2° for α and derive the errors for T_s and T_1 directly from the exponential fits.

To determine the charge-carrier density, we measured the power in front of (P_0) and behind the sample ($P_{\text{transmitted}}$) for each measurement. From these data, we calculate the absorption of the sample using Fresnel formulas. For this, we estimate the

reflection loss of the cryostat windows to 6% and assume a refractive index of 3.5 for GaAs. We obtain the relative sample absorption x by taking care of the reflection losses at the interfaces and considering a double pass through the sample via

$$\begin{aligned} & P_0 \times 0.94 \times \left(1 - \left(\frac{2.5}{4.5} \right)^2 \right) \times (1 - x) \times \left(1 - \left(\frac{2.5}{4.5} \right)^2 \right) \\ & \times 0.94 + P_0 \times 0.94 \times \left(1 - \left(\frac{2.5}{4.5} \right)^2 \right) \times (1 - x) \\ & \times \left(\frac{2.5}{4.5} \right)^2 \times (1 - x) \times \left(\frac{2.5}{4.5} \right)^2 \times (1 - x) \\ & \times \left(1 - \left(\frac{2.5}{4.5} \right)^2 \right) \times 0.94 \\ & = P_{\text{transmitted}} \end{aligned} \quad (3)$$

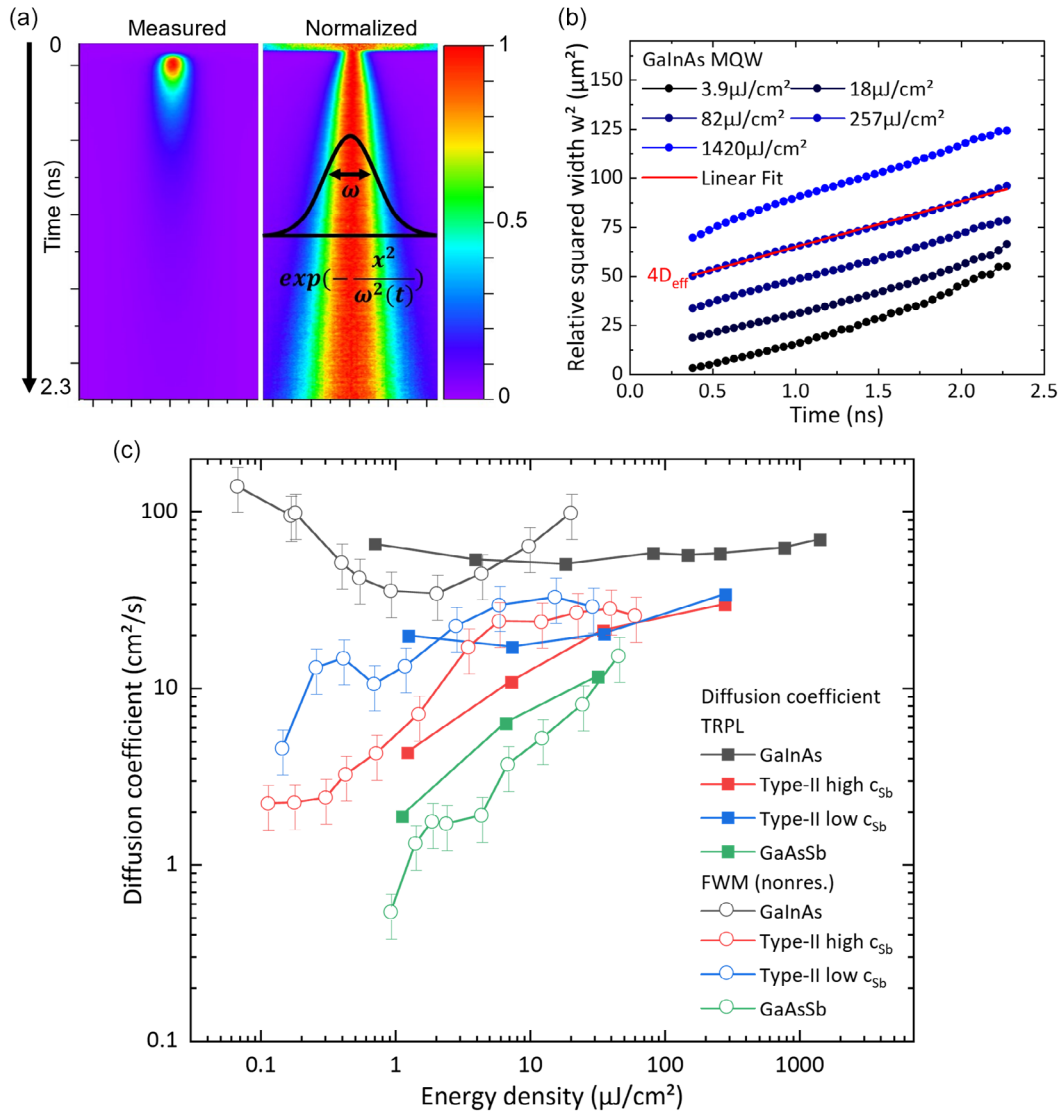


Figure 3. a) TRPL spatial imaging before (left panel) and after (right panel) amplitude normalization for each time step. The spatial line broadening due to diffusion is more prominently visible in the normalized image. b) The time-dependent spatial width of photoluminescence for the regular (Ga,In)As multiple quantum-well at various excitation densities. The increase in spatial width is observed to be independent of the excitation density. c) Diffusion coefficient obtained from the TRPL and nonresonant FWM measurements (hollow circles) for various excitation densities.

The charge-carrier density then results from

$$\text{Charge-carrier density} = \frac{P_0 \times x}{\text{Laser repetition rate}} \times \frac{\lambda}{h \times c} \quad (4)$$

$$\times \frac{1}{\text{Spot size}} \times \frac{1}{\text{\#Quantum wells}}$$

The diffusion coefficients resulting from the variation in charge-carrier density by four orders of magnitude for the (Ga,In)As type-I sample are $(14.5\text{--}41.1)\text{ cm}^2\text{ s}^{-1}$ for resonant excitation and $(34.2\text{--}139.3)\text{ cm}^2\text{ s}^{-1}$ for nonresonant excitation. They are summarized in Figure 2c. This agrees well with the diffusion coefficients reported in the literature for conceptually very similar GaAs quantum-well samples in the range of $(15\text{--}80)\text{ cm}^2\text{ s}^{-1}$.^[20–22] Overall, no clear trend of the diffusion

coefficient as a function of charge-carrier density is found in this sample. The diffusion coefficients for the other type-I sample consisting of Ga(As,Sb) quantum wells, however, increase almost linearly with density for nonresonant excitation. They range from $0.5\text{ cm}^2\text{ s}^{-1}$ at a charge-carrier density of $7.2 \times 10^{10}\text{ cm}^{-2}$ to $15.1\text{ cm}^2\text{ s}^{-1}$ at $5.0 \times 10^{12}\text{ cm}^{-2}$. The observed behavior of the diffusion coefficient has been attributed in the literature to various causes, including scattering with phonons,^[21,22] carrier–carrier scattering, carrier degeneracy,^[23–25] interface-roughness scattering,^[26] or localized states.^[27,28] Since our samples are structurally similar, with all quantum wells made of GaAs with small additions of In or Sb and embedded in GaAs, it is expected that most of these causes would affect the (Ga,In)As quantum-well sample as well. However, the absence of distinct density-dependent diffusion in the (Ga,In)As sample suggests

that scattering with phonons, carrier–carrier scattering, or carrier degeneracy may not account for the observed density-dependent behavior of the diffusion coefficient, as these effects would likely occur similarly in all samples.

Instead, we hypothesize that the effects of sample quality, such as interface roughness and localized states, may be responsible for the observed density-dependent behavior of diffusion, as these effects can vary between samples and impact them differently. In support of this hypothesis, we note that although the temperature-dependent PL indicates good quality for all samples, differences in the inhomogeneous linewidth of the exciton resonances in the linear absorption spectra can be observed. Localized states can arise from impurities, compound fluctuations, or well-width variations, which are known to be related to interface roughness. Both localized states and interface roughness can increase the inhomogeneous linewidths of samples.

In particular, we observe a significantly larger inhomogeneous exciton linewidth in the linear absorption spectra of the Ga(As, Sb) quantum-well sample compared to the (Ga,In)As quantum-well sample. This suggests that the Ga(As,Sb) quantum-well sample may have a higher density of localized states compared to the (Ga,In)As quantum-well sample. At low excitation densities, the charge carriers are likely trapped by these localized states, impeding their diffusion. However, as the carrier density increases, these localized states become predominantly occupied, allowing additional charge carriers to diffuse more freely.^[22] This results in an increase of the diffusion coefficient with density.^[27,28] The diffusion coefficient for the Ga(As,Sb) quantum wells shows a positive correlation with the charge-carrier density also under resonant excitation conditions. It should be noted, however, that the measurements for resonant excitation are performed only at comparatively high carrier densities, that is, in the region where the exciton-Mott transition is expected to occur. In this sample, the measurement of exciton diffusion is hindered by the relatively low exciton absorption.^[10,29,30] Thus, on the one hand, a lot of light is needed to generate the respective charge-carrier densities which, together with the low absorption, leads to a lot of disturbing stray light in the PDs. On the other hand, the changes in the sample caused by the density grating are small and hence comparatively little signal is diffracted in $\vec{k}_3 + (\vec{k}_2 - \vec{k}_1)$. Accordingly, we assume that we do not observe exciton diffusion in this density range for resonant excitation conditions but rather the diffusion of a free electron–hole plasma. Consequently, the diffusion coefficients fit very well to the values for nonresonant excitation since both cases monitor the diffusion of an electron–hole plasma. After resonant excitation, the diffusion coefficient ranges from $5.9 \text{ cm}^2 \text{ s}^{-1}$ for an excitation density of $1.4 \times 10^{12} \text{ cm}^{-2}$ and increases to $82.0 \text{ cm}^2 \text{ s}^{-1}$ for an excitation density of $4.4 \times 10^{13} \text{ cm}^{-2}$. Thus, the diffusion coefficients for the highest excitation densities are comparable to the results for the (Ga,In)As quantum-well sample.

Next, we consider the type-II heterostructures to study the influence of internal interfaces on diffusion.

Notably, we find a similar pattern for the type-II heterostructures as for the Ga(As,Sb) quantum-well sample. The diffusion coefficient for both type-II samples increases with density after nonresonant excitation. They range from $2.2 \text{ cm}^2 \text{ s}^{-1}$ ($4.5 \text{ cm}^2 \text{ s}^{-1}$) for an excitation density of $6.1 \times 10^9 \text{ cm}^{-2}$

($5.1 \times 10^9 \text{ cm}^{-2}$) for the sample with the higher (lower) Sb content to $28.1 \text{ cm}^2 \text{ s}^{-1}$ ($32.7 \text{ cm}^2 \text{ s}^{-1}$) for an excitation density of $1.9 \times 10^{12} \text{ cm}^{-2}$ ($5.4 \times 10^{11} \text{ cm}^{-2}$), which is comparable to other studies of type-II structures.^[31] The increase of the diffusion coefficient with excitation density is stronger for the sample with the higher Sb content which corresponds to the larger inhomogeneous exciton linewidth in the linear absorption. This corroborates the idea that the saturation of localized states due to increasing excitation density contributes to the rise of diffusion coefficients. Improved sample quality results in smaller inhomogeneous linewidths of exciton resonances, which leads to reduced reliance of the diffusion coefficient on the excitation density. We observe a lower diffusion for resonant excitation of the CTXs than for nonresonant excitation. This is consistent with the results obtained for the (Ga,In)As quantum-well sample. Given that the exciton formation dynamics in the samples under investigation are well established,^[10,32] it is known that exciton formation takes place continuously on a timescale of hundreds of picoseconds. The transient grating arising from nonresonant excitation decays on a shorter timescale, suggesting that primarily an electron–hole plasma diffuses in this case. Conversely, we observe exciton diffusion following resonant excitation. In principle, the exciton diffusion behaves like the electron–hole plasma diffusion but displays an overall lower level of diffusion coefficients. Here, calculations based on a transport model show that scattering with acoustic phonons have a stronger impact on the mobility of excitons than on that of an electron–hole plasma.^[33] Also, scattering with fluctuations within the quantum-well barriers are expected to have a stronger effect on excitons.^[34] Furthermore, a higher diffusion coefficient with increasing excitation energy has already been observed on GaAs quantum wells.^[29] Overall, the observed lower diffusion coefficient of excitons thus agrees very well with the expectations based on previous experimental results as well as on transport model calculations.

We use TRPL imaging as a complementary method to corroborate our findings and determine the diffusion coefficients. The time-dependent spatial broadening of the PL clearly reveals the diffusion, as shown in the right panel of Figure 3a. The diffusion coefficients are calculated from the time dependence of the spatial width of the PL according to^[17]

$$w^2(t) = w_0^2 + 4 \times D_{\text{eff}} \times t \quad (5)$$

The squared width $w^2(t)$ is obtained from the Gaussian distribution function $e^{-\frac{x^2}{w^2(t)}}$. The diffusion coefficient is determined by fitting a linear regression to the plot of $w^2(t)$ with a slope of $4 \times D_{\text{eff}}$ (cf. Figure 3b).

Figure 3c summarizes the diffusion coefficients obtained from both TRPL and nonresonant FWM measurements. The TRPL data yield effective diffusion coefficients in the ranges of $(50.5\text{--}70.0) \text{ cm}^2 \text{ s}^{-1}$ (type-I (Ga,In)As), $(4.3\text{--}26.3) \text{ cm}^2 \text{ s}^{-1}$ (type-II high Sb), $(17.1\text{--}33.9) \text{ cm}^2 \text{ s}^{-1}$ (type-II low Sb), and $(1.9\text{--}11.6) \text{ cm}^2 \text{ s}^{-1}$ (type-I Ga(As,Sb)). The results from both methods are very similar, with some values virtually coinciding, which emphasizes the reliability of the obtained data.

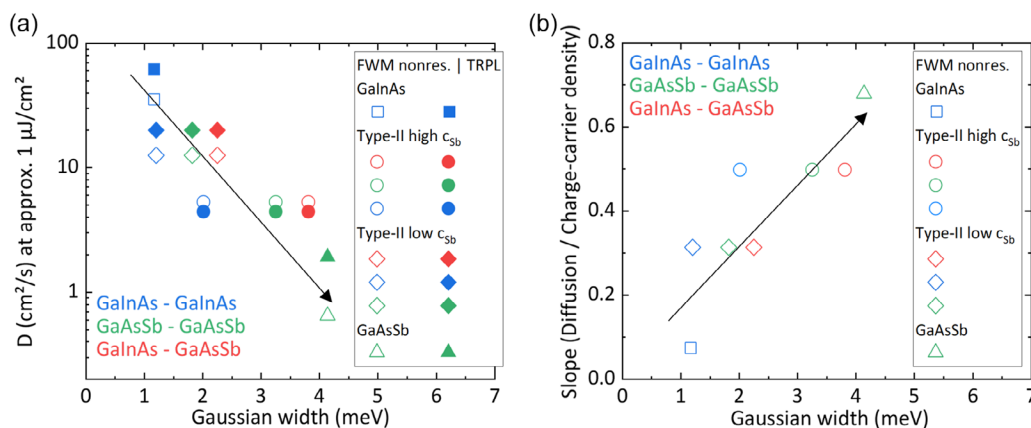


Figure 4. a) The diffusion coefficient at an excitation density of 1 μJ cm⁻² plotted against the associated Gaussian widths obtained from the absorption spectra. The data, acquired from both TRPL and FWM measurements, reveal a clear trend where larger Gaussian linewidths correspond to smaller diffusion coefficients. b) The average slope of the diffusion coefficient normalized to the charge-carrier density, obtained from nonresonant FWM measurements, plotted against the Gaussian widths.

The observed trend in all measurements is that smaller inhomogeneous linewidths lead to larger diffusion coefficients and lower density-dependent slopes of the diffusion coefficient.

Figure 4a illustrates the diffusion coefficients of the individual samples at an excitation density of approximately 1 μJ cm⁻² as a function of the inhomogeneous linewidth of the exciton transitions in the absorption. The data include the inhomogeneous linewidth of all three exciton resonances of the type-II samples. In general, the diffusion coefficient decreases as the inhomogeneous linewidth increases. A comparable trend is also observed in 2D materials.^[35] In particular, our data suggest that the sample quality, specifically the inhomogeneous linewidth, is more critical than the effects of the internal interface. Consistently, the diffusion coefficients of the two type-II heterostructures concur with their average type-II exciton linewidth, resulting in the anti-proportional trend shown in Figure 4a. If the internal interface had a significant impact on diffusion beyond its influence on the inhomogeneous linewidth via interface roughness, the diffusion coefficient for the type-II samples in Figure 4a would fall significantly below the trend line linking the data of the two type-I structures. However, we do not observe this behavior. In addition, we observe a linear relationship between the slope of the diffusion coefficient and the inhomogeneous linewidth (Figure 4b). We identify this trend as a measure of the amount of localized states in the sample. Interestingly, we find that the increase of the diffusion coefficient with increasing charge-carrier density is linearly correlated to the inhomogeneous linewidth, regardless of having type-I or type-II heterostructures. Based on our results, we can conclude that the charge-carrier transport along the interface is primarily affected by the sample quality, as indicated by the exciton linewidth and associated density of localized states, rather than the internal interface.

5. Conclusion

In summary, we determine the effective diffusion coefficients of type-I ((Ga,In)As, Ga(As,Sb)) multiple quantum-well structures

and type-II ((Ga,In)As-Ga(As,Sb)) heterostructures using FWM spectroscopy and space- and TRPL. Our findings demonstrate that the diffusion of excitons is lower compared to free electron-hole pairs, regardless of whether they are regular excitons or CTXs. Moreover, we identify a strong correlation between the sample quality, represented by the inhomogeneous broadening of the exciton linewidth in linear absorption spectroscopy, and the diffusion coefficient, as well as the increase of the diffusion coefficient with the charge-carrier density. We observe that the internal interfaces in the type-II heterostructures have less impact on the lateral carrier transport than the sample quality. Thus, our findings suggest that interfaces are not the limiting factor in miniaturized structures, as long as the quality of the semiconductor layer is maintained, despite the proximity to interfaces.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

charge-carrier transport, charge-transfer excitons, diffusion, internal interfaces, semiconductor heterostructures

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