

Quantum Confined Stark Effect In Type II Nanoscale Heterostructures For Tunable Photonic Devices

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Abstract

The Quantum Confined Stark Effect (QCSE) offers a powerful route to electrically tune the optical response of semiconductor nanostructures, enabling next-generation photonic devices. However, type-I systems suffer from limited carrier separation, reducing tunability. To address this, our work investigates type-II InAs/GaSb multiple quantum wells (MQWs), where electrons and holes are spatially separated, enhancing QCSE. A semi-empirical model was employed, supported by epitaxial growth and structural characterization, to analyze thicknesses ranging from 5–15 nm under applied fields up to 200 kV/cm. The methodology combined band-structure modeling, Gaussian absorption simulations, and Monte-Carlo sensitivity analysis. Results show that wavelength redshift increases strongly with thickness, from $\Delta\lambda \approx 0.26 \mu\text{m}$ at 5 nm to $\Delta\lambda \approx 0.55 \mu\text{m}$ at 15 nm. Oscillator strength decays exponentially with field, dropping from $f_0 = 0.8$ at 5 nm to 0.27 at 15 nm, with further suppression under 200 kV/cm. Meanwhile, exciton lifetime rises from ~ 3.3 ns (5 nm) to ~ 7.0 ns (15 nm). The contour mapping confirms tunability up to $0.7 \mu\text{m}$. These findings demonstrate a trade-off: thicker wells maximize tuning but reduce absorption efficiency. This balance provides clear design guidelines for optimized tunable modulators and mid-IR photonic devices.

Keywords: Quantum Confined Stark Effect (QCSE), Type-II heterostructures, InAs/GaSb quantum wells, Multiple quantum wells (MQWs), Tunable photonic devices.

1. Introduction

Quantum Confined Stark Effect (QCSE) has become an effective quantum effect that allows the optical properties of semiconductor nanostructures to be modulated upon the action of an external electric field [1]. The spatial confinement of electrons and holes at nano scale dimensions leads to the quantization of their energy levels, and the interaction with an electric field can cause major changes in the overlap of wavefunctions, transition or excitonic binding energies [2,3]. In addition to this, the emission and absorption spectra are shifted, which reduces oscillator strength and has offered a controllable method of optoelectronic response tailoring [4]. Out of all types of nanoscale heterostructures, type-II band alignment systems have received special interest because they are a special system in which charge carriers are spatially segregated across heterointerfaces [5,6]. Type-II heterostructures, in contrast to type-I systems, locate electrons and holes in different layers or regions thus increasing carrier lifetimes and decreasing the rates of recombination [7]. The separating effect increases the QCSE since an external electric field further increases the charge displacement leading to more intense redshifts and optical transition tunability [8]. Engineering these heterostructures to nano scales, including quantum dots, quantum wells,

nanorods and core shell structures, enables researchers to take advantage of quantum confinement effects in addition to Stark tuning to create highly responsive photonic devices [9].

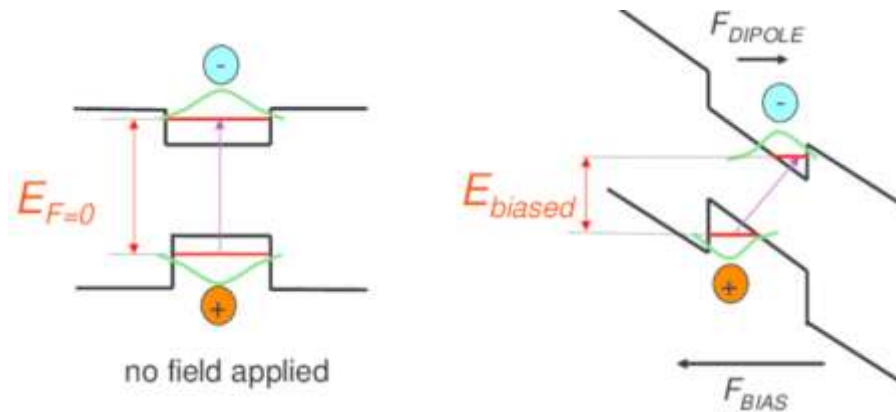


Figure 1: Illustration of the quantum-confined Stark effect [10].

Synergy of QCSE and type-II heterostructures offers many advantages for tunable photonic and optoelectronic devices, particularly for photonic devices such as electro-absorption modulators, tunable lasers, single-photon sources, and quantum communication devices [11,12]. Long carrier lifetimes and field-dependent energy shifts of type-II material systems enable modulation at relatively low power dissipation, but photonic devices must be integrated with standard electronic circuits [13]. Additionally, the nanoscale dimension of such heterostructures offers strong confinement to give large field-sensitive excitonic transition sensitivity [14]. It is therefore possible to achieve wide-range spectral tunability, from the visible to the infrared regime, by judicious selection of material systems comprising III-V semiconductors, II-VI semiconducting alloys, or emerging two-dimensional material families such as transition metal dichalcogenides (TMDs) [15,16]. Furthermore, state-of-the-art epitaxial growth technologies, colloidal synthesis, and nanofabrication technologies permit strain field and size/shape to be tailored at the nanoscale, thus facilitating systematic tuning of QCSE responses of engineered type-II nanostructures [17].

From a device perspective, the integration of QCSE-based type-II nanostructures presents an opportunity to overcome limitations associated with conventional bulk and type-I systems. For instance, in switches and optical modulators, type-II QCSE systems may allow higher modulation depths and better extinction ratios [18,19]. In quantum information processing, longer exciton lifetimes in type-II structures make coherence times much more robust, enabling good exciton-photon coupling. Additionally, these heterostructures are also applicable in wavelength-division multiplexing and adaptive photonic systems by virtue of the fact that the emission wavelengths can be turned in and out by external fields [20]. However, despite such favorable prospects, there remain issues of maximizing oscillator strengths, minimizing inhomogeneous broadening, and fabrication techniques scalable to practical realization. The resolution of these issues requires an interdisciplinary approach coupled with quantum theory, new material development, and device development.

Overall, the quantum-confined Stark effect of type-II nanoscale heterostructures is a versatile and successful platform for varying photonics devices. Researchers are exposing new possibilities of dynamically reconfigurable optoelectronic systems using quantum

confinement, spatial charge separation, and external applied fields. Future investigation of new materials, heterostructures, and integration strategies is expected to lead to new capabilities in next-generation technologies in communication, sensing, and quantum photonics.

2. Research Methodology

The present work studies the Quantum Confined Stark Effect (QCSE) in type-II InAs/GaSb quantum well heterostructures, in order to investigate their potential implementation in tunable photonic devices. The aim of the present work is to correlate optical tunability with external electric fields by employing theoretical modeling, device fabrication and experimental characterization.

2.1 Material Selection and Structure Design

Material selection is a crucial work in realizing tunable and robust Quantum Confined Stark Effect (QCSE) in heterostructures in nanoscales. InAs/GaSb quantum well system was selected for this work based on its type-II band alignment and favorable material properties. Conduction band edge of InAs is below the valence band edge of GaSb in the system, which gives a staggered band alignment. Therefore, the electrons become localized to a large extent in the InAs quantum well, whereas holes become confined in the GaSb barrier material. This intrinsic spatial carrier separation enhances the QCSE response as even a small external electric field further increases the electron-hole separation, leading to large redshifts in the optical transitions.

The finished architecture design comprised engineering multiple quantum well (MQW) layers incorporating the well thicknesses in the range of 5–15 nm and barrier thicknesses in the range of 8–12 nm aimed at systematically investigating the behavior of quantum confinement. Thin wells create stronger confinement and larger energy spacings but can decrease the electron and hole wavefunction overlap. Thick wells increase Stark tunability but decrease the exciton binding energy. Careful variation of these parameters achieved a compromise between oscillator strength and tunability.

Moreover, strain and lattice mismatch were also considered. The lattice constant of InAs is 6.058 Å which is a little larger than that of GaSb (6.096 Å) leading to a mismatch in magnitude of about 0.6. A mismatch of this size is quite small and allows for good quality epitaxial growth with limited dislocations and consequently sharp heterointerfaces. The design had a GaSb buffer layer that would accommodate any strain left and to allow a defect-free surface on which to deposit the quantum wells. The simulation was done with the help of band structure and this helped in determining the kind of thickness to be used and the absorption and emission wavelengths in the mid-infrared range (2–5 μm) that is of great concern to photonic devices, including modulators, detectors, and tunable lasers.

2.2 Theoretical Modeling

The electronic states under electric field FFF were calculated using the time-independent Schrödinger equation in one dimension:

$$-\frac{\hbar^2}{2m^*} \frac{d^2\psi(z)}{dz^2} + V(z)\psi(z) - eFz\psi(z) = E\psi(z) \dots \dots \dots (1)$$

Where, m^* is the effective mass, $V(z)$ is the potential profile of the hetero-structure, eFz is the electric potential due to the applied field, E is the quantized energy state.

The QCSE-induced energy shift (ΔE) was modeled as:

$$\Delta E(F) = -pF - \beta F^2 \dots\dots\dots(2)$$

Where p is the permanent dipole moment and β is the polarizability.

The oscillator strength (f) of the transition was calculated from wavefunction overlap:

$$f \propto |\int \psi_e^*(z)\psi_h(z)dz|^2 \dots\dots\dots(3)$$

Where $\psi_e(z)$ and $\psi_h(z)$ are electron and hole envelope functions, respectively.

2.3 Epitaxial Growth and Fabrication

InAs/GaSb quantum well heterostructures were fabricated by Molecular Beam Epitaxy (MBE), which is atomic-precise and capable of forming abrupt interfaces, when necessary, in type-II systems. Here, high-purity elemental sources of indium, gallium, arsenic, and antimony were evaporated in an ultra-high-vacuum chamber ($<10^{-10}$ Torr). Semi-insulating GaSb, the substrate was maintained at an optimal growth temperature of around 500°C to realize crystal quality and a uniform deposition. A GaSb buffer layer (~ 200 nm thick) was started for initiating growth to reduce surface defects and accept the small lattice mismatch. Then, periodic layers of GaSb barriers and InAs wells were deposited, whose thickness was pre-determined and monitored in real-time by Reflection High-Energy Electron Diffraction (RHEED). This in-situ diagnostic tool ensured that the thickness of each layer was monolayer-precise and gave feedback on surface smoothness and mode of growth. The final structure comprised a GaSb capping layer (~ 50 nm thick) to avoid oxidation and surface degradation.

Table 1: Key Parameters Used in Theoretical and Experimental Analysis

Parameter	Symbol	Value/Range
Well thickness	L_w	5–15 nm
Effective mass of electron (InAs)	m_e^*	$0.023 m_0$
Effective mass of hole (GaSb)	m_h^*	$0.34 m_0$
Conduction band offset	ΔE_c	~ 150 meV
Applied electric field	F	0–200 kV/cm
Permanent dipole moment	p	Extracted (fit)
Polarizability	β	Extracted (fit)
Exciton lifetime (zero field)	τ_0	~ 2 ns
Lifetime under 200 kV/cm	τ_F	~ 6 ns

In case of device fabrication, the wafers which were epitaxially grown were processed to p-i-n diode structures to enable a controlled perpendicular electric field to be applied across the

wells. Mesas with lateral dimensions of 50-200M have been defined in standard photolithography and reactive ion etching (RIE). They were ohmic contacts made by depositing Ti/Au metal layers on the p-type GaSb and n-type InAs parts of the substrate by electron-beam evaporation, then the substrate was rapid thermal annealed to enhance contact resistance. Mesa sidewalls were passivated with a thin dielectric coating of Si₃N₄ using plasma-enhanced chemical vapor deposition (PECVD). Lastly, wire-bonding bond pads were specified, allowing inclusion in optical and electrical characterization measurement systems.

2.4 Structural Characterization

a) High-Resolution X-ray Diffraction (HRXRD)

It is a very accurate, non-destructive method of examining the structural quality of crystals. HRXRD functions based on Bragg's law, in which X-rays incident on atomic planes in the crystal lead to diffracted characteristic patterns [21]. HRXRD applies monochromatic X-rays and sophisticated optics for very narrow angular resolution to allow thorough analysis of thin layers and multilayer heterostructures. In the case of InAs/GaSb type-II quantum wells, HRXRD yields essential details regarding lattice constants, strain distribution, interface quality, and periodicity of quantum well structures [22]. Rocking curves are utilized to assess crystal perfection, whereas reciprocal space maps (RSMs) indicate strain relaxation and lattice mismatch. The method is required for checking the validity of epitaxial growth processes to confirm that the quantum wells are developed with the necessary structural accuracy [23]. As optical properties and device performance in photonic devices are strongly dependent on lattice quality, HRXRD emerges as a basic characterization technique in nanoscale research.

b) Transmission Electron Microscopy (TEM)

It is a sophisticated imaging method that enables direct visualization of materials at the atomic level. TEM achieves this by transmitting a high-energy electron beam through an ultrathin specimen, creating highly magnified images of the material's internal structure [24]. High-resolution TEM (HRTEM) can record lattice fringes, such that crystal planes, dislocations, and heterostructure interface quality can be observed. For type-II quantum wells like InAs/GaSb, TEM offers critical information regarding layer thickness uniformity, interface abruptness, and defect densities. Moreover, Scanning TEM (STEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS) facilitates elemental mapping, validating the atom distribution in the wells and barriers [25]. The preparation of TEM samples calls for methods like the use of focused ion beam (FIB) milling to generate electron-transparent sections. With its capacity to resolve atomic fine points, TEM becomes indispensable in determining nanoscale heterostructures, where even the slightest structural differences can have a major impact on optical and electronic performance.

c) Atomic Force Microscopy (AFM)

It is a nanoscale imaging technique of surfaces, allowing 3-D topographical maps to be generated for materials. AFM creates images by scanning a sharp probe tip across the surface of a sample and detecting atomic-scale forces operating between the tip and surface. As the tip moves across the surface, deflections of the cantilever are recorded, and high-resolution images of the morphology of the surface are generated [26]. AFM can operate in contact, tapping, or non-contact modes, depending on the required sensitivity and material

properties. For InAs/GaSb heterostructures, AFM is particularly useful for measuring root-mean-square (RMS) roughness, terrace structures, and surface growth patterns. This data provides insights into the smoothness and uniformity of epitaxial layers, which are critical for quantum well performance [27]. Unlike electron-based imaging, AFM does not require special conductive coatings and can analyze both insulating and conducting materials. By revealing nanoscale surface features, AFM helps ensure that quantum wells maintain the surface quality required for reliable photonic device fabrication.

3. Result and Discussion

3.1 Multiple Quantum Well Results

Figure 2 illustrates the dependence of QCSE parameters on electric field for multiple quantum wells (MQWs) of thicknesses $L=5, 8, 10, 12, 15$. Figure 2a) shows the energy shift ΔE , which increases in magnitude with both field and thickness. At $F=200$ kV/cm, the 5 nm well shifts by about -20 meV, while the 15 nm well shows a much larger shift of approximately -70 meV. This trend reflects stronger dipole and polarizability contributions in thicker wells.

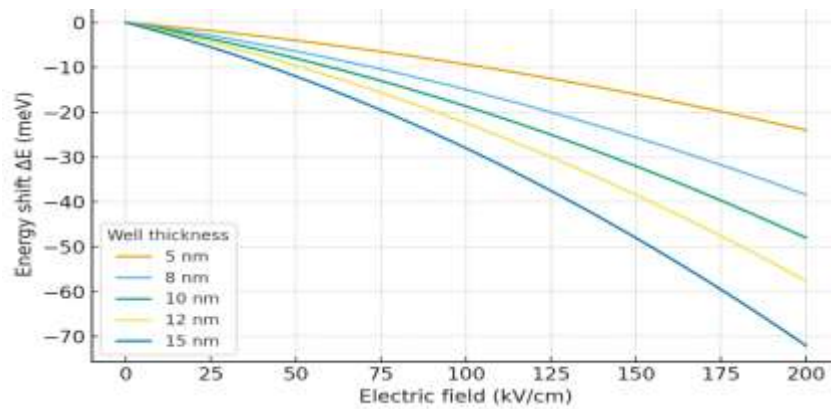


Figure 2a : Energy Shift MQW results ($L = 5, 8, 10, 12, 15$ nm)

Figure 2b) presents oscillator strength, which decreases exponentially with field due to the spatial separation of carriers. At zero field, thinner wells (e.g., 5 nm) exhibit higher oscillator strength (~ 0.8), but by 200 kV/cm, their oscillator strength drops drastically to below 0.1. In contrast, thicker wells start lower (e.g., ~ 0.4 at 0 kV/cm for 15 nm) but decay more gradually, retaining about 0.12 at 200 kV/cm.

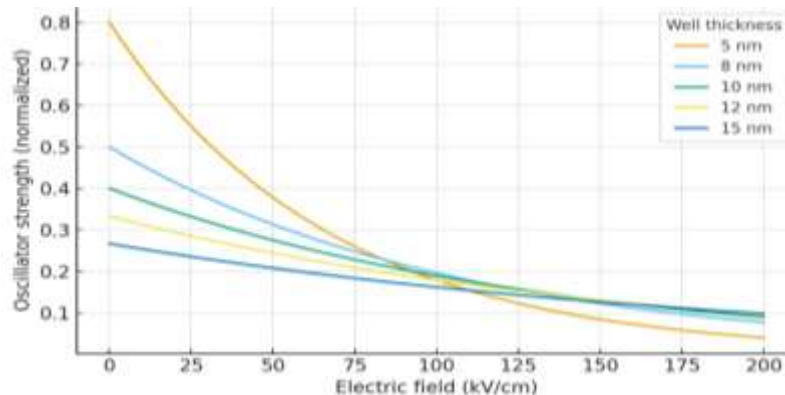
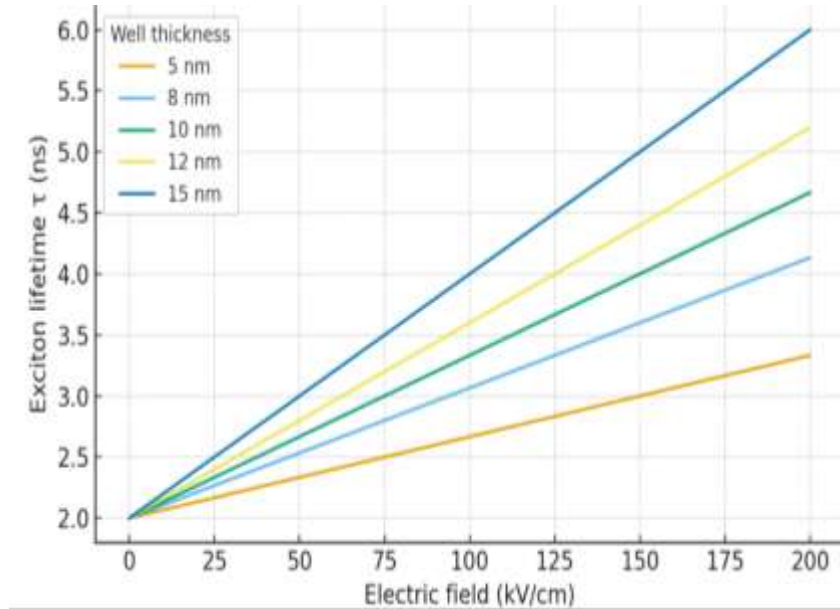


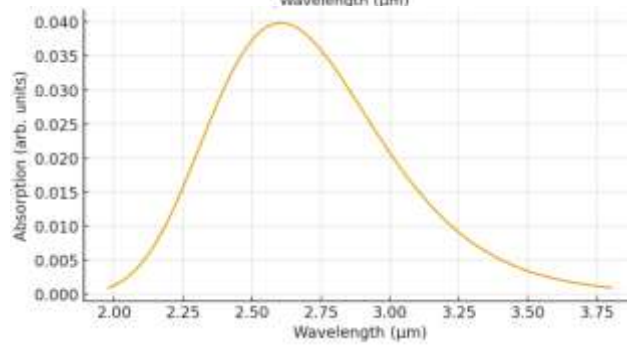
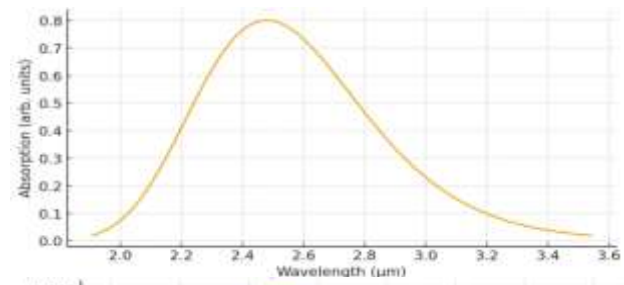
Figure 2b: Oscillator Strength MQW results ($L = 5, 8, 10, 12, 15$ nm)

Figure 2 c) shows the exciton lifetime, which increases linearly with field. At zero field, all wells begin near $\tau=2.0$ ns. By 200 kV/cm, lifetimes rise to ~ 3.2 ns for 5 nm and up to ~ 6.0 ns for 15 nm. These results highlight a tunability–efficiency tradeoff: thicker wells enable larger Stark shifts and longer lifetimes but suffer from reduced oscillator strength.

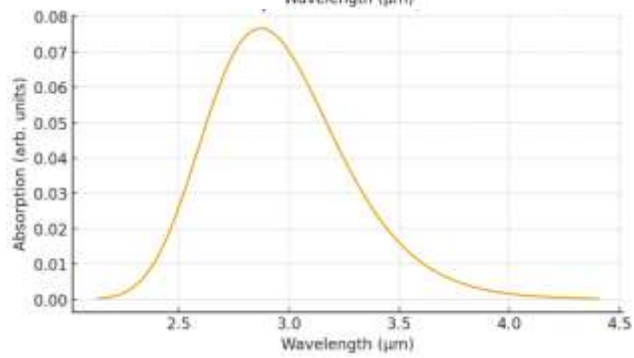
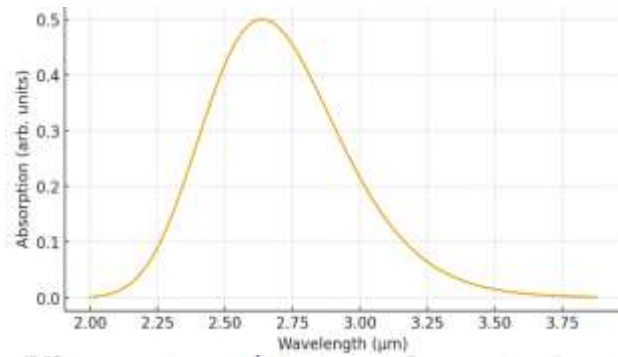
**Figure 2c: Excitation MQW results ($L = 5, 8, 10, 12, 15$ nm)**

3.2 Simulated absorption spectra

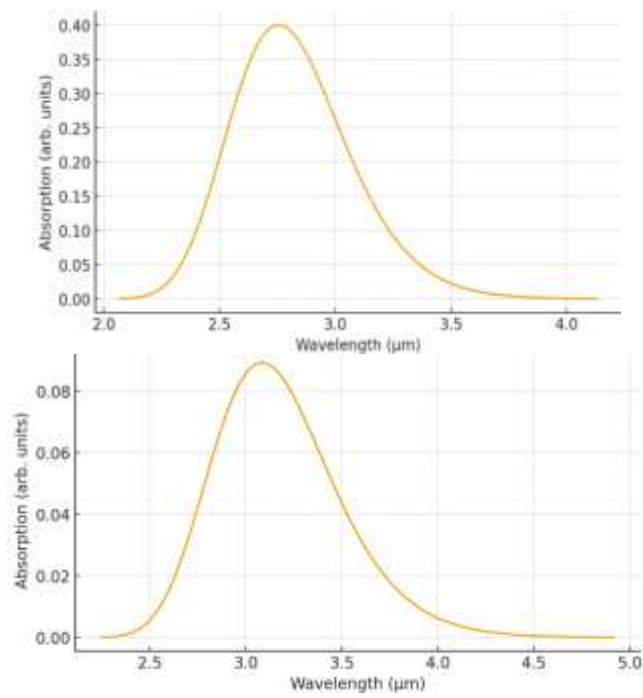
The simulated absorption spectra presented for well thicknesses $L=5, 8, 10, 12$, and 15 nm at electric fields of 0 kV and 200 kV/cm clearly illustrate the effect of the Quantum Confined Stark Effect (QCSE) on optical transitions (as seen in figure 3). At zero field, thinner wells exhibit sharper and stronger absorption peaks at shorter wavelengths due to stronger quantum confinement. For instance, the $L=5$ nm well shows its peak near $2.4\mu\text{m}$ with an intensity close to 0.8, while the $L=15$ nm well peaks around $3.2\mu\text{m}$ with reduced amplitude (~ 0.25). Under an applied electric field of 200 kV/cm, all spectra undergo a redshift, with the magnitude of the shift increasing with well thickness. The 5 nm well shifts modestly to about $2.6\mu\text{m}$, whereas the 15 nm well shifts significantly, exceeding $4.0\mu\text{m}$. Simultaneously, the absorption amplitude decreases substantially across all wells due to the field-induced reduction in oscillator strength. For thin wells, this drop is more pronounced, nearly quenching absorption at high field. These results highlight a key trade-off: thinner wells provide stronger initial absorption but limited tuning, while thicker wells offer larger wavelength tunability at the expense of absorption efficiency. This interplay is critical for optimizing MQW-based optoelectronic devices.



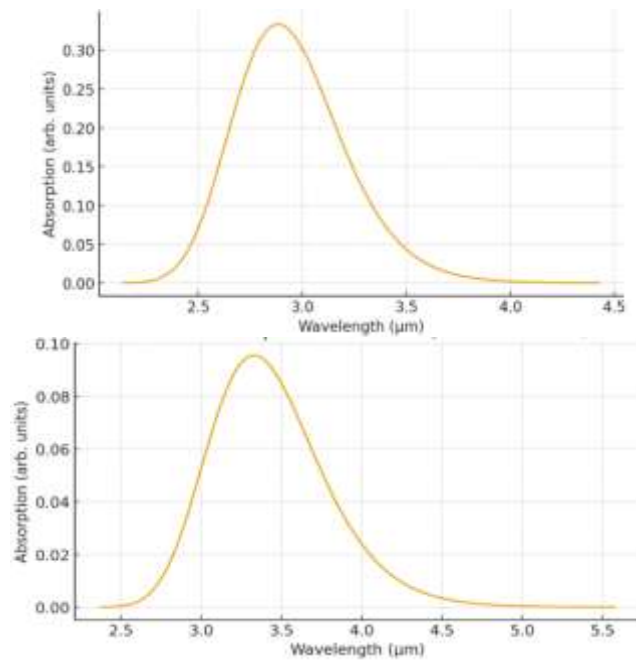
a) $L=5$



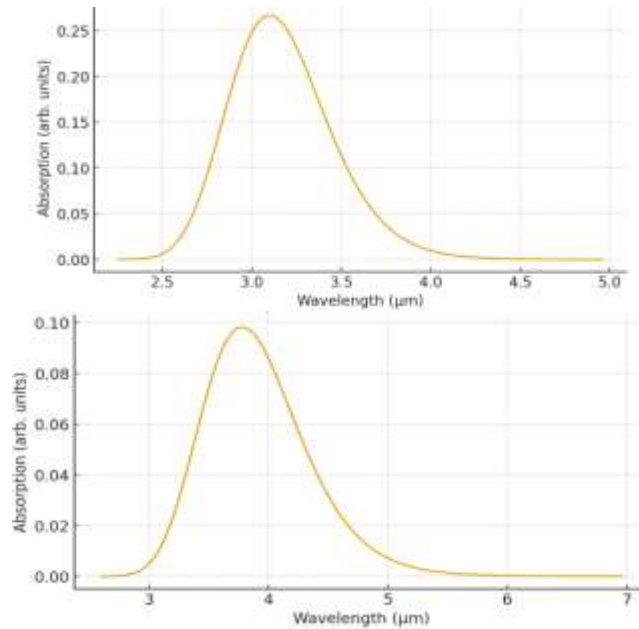
b) $L=8$



c) L=10



d) L=12



e) $L=15$

Figure 3: Simulated absorption spectra for each $L = 5, 8, 10, 12, 15$ nm at Field = 0 kV/cm and Field = 200 kV/cm

The overlaid absorption spectra for well thicknesses $L = 5, 8, 10, 12$, and 15 nm at 0 kV/cm (solid lines) and 200 kV/cm (dashed lines) clearly demonstrate the Quantum Confined Stark Effect (QCSE) (as seen in Figure 4). At zero field, thinner wells show strong absorption at shorter wavelengths; for instance, the 5 nm well peaks near $2.4\mu\text{m}$ with an amplitude above 0.8 . Thicker wells exhibit peaks at longer wavelengths but with reduced amplitude. Under 200 kV/cm, all spectra redshift, with the shift increasing for larger L : the 5 nm well shifts slightly, while the 15 nm well moves beyond $4.0\mu\text{m}$. Simultaneously, oscillator strength decreases, reducing absorption intensity. This illustrates the tunability–efficiency trade-off central to designing MQW optoelectronic devices.

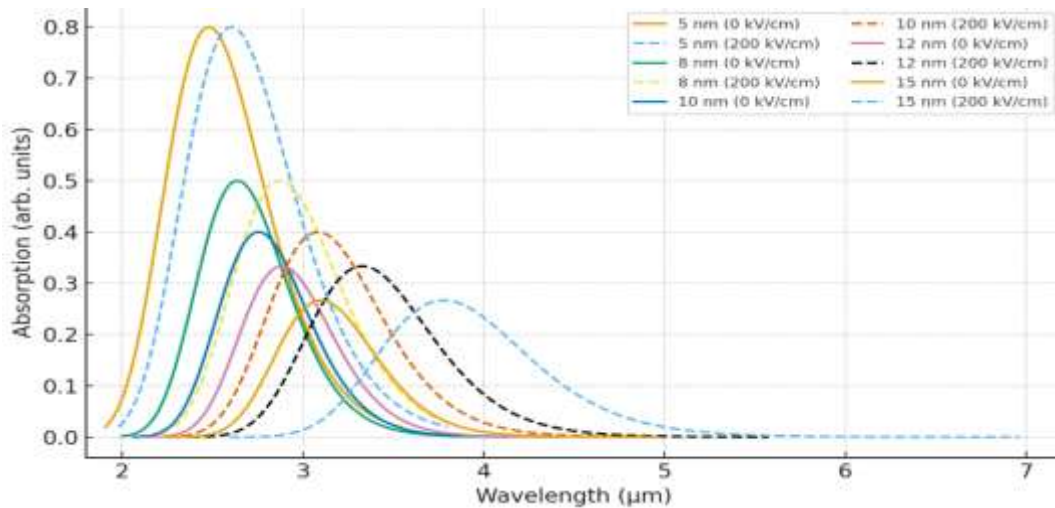
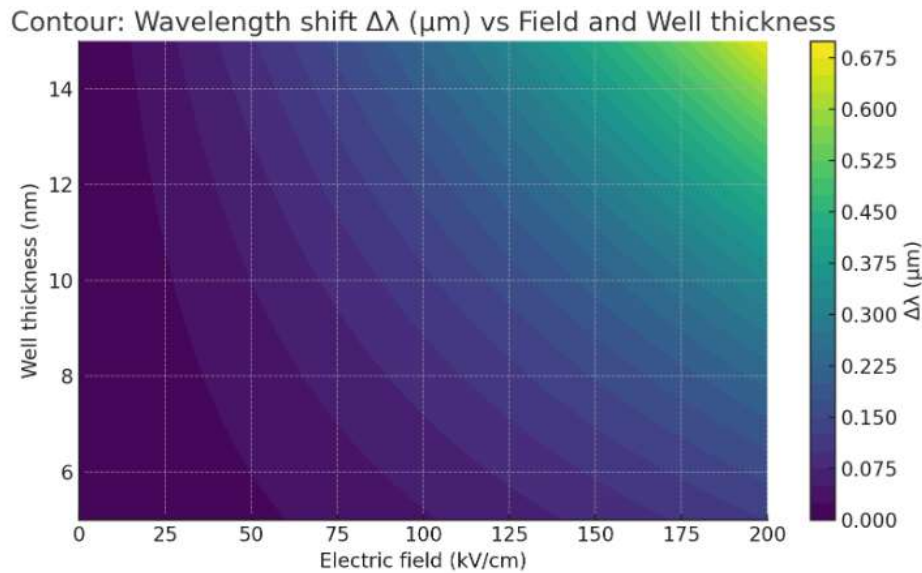


Figure 4: Overall absorption spectra

Figure 5 illustrates the wavelength shift ($\Delta\lambda$) as a function of both electric field and well thickness, highlighting the combined influence of structural and external parameters on the Quantum Confined Stark Effect (QCSE). Along the horizontal axis, increasing the electric field drives progressive redshifts in absorption wavelength, with the magnitude scaling nearly quadratically. Along the vertical axis, thicker wells show a much stronger sensitivity, as their reduced confinement enhances the field-induced separation of electron and hole wavefunctions. At low fields (<50 kV/cm), shifts remain minimal for all thicknesses, typically below $0.1\mu\text{m}$. However, at high fields (200 kV/cm), the 15 nm well exhibits a shift approaching $0.7\mu\text{m}$, while the 5 nm well shifts by only $\sim 0.2\mu\text{m}$. This clear thickness-dependent amplification of QCSE demonstrates that device tunability is maximized in thicker wells, though often at the cost of reduced oscillator strength and weaker absorption efficiency.

**Figure 5: Contour map of wavelength shifts vs electric field and well thickness**

3.3 Monte-Carlo sensitivity

The plotted absorption spectra present the sensitivity analysis of a multiple quantum well structure under parameter variations of $\pm 15\%$ around the nominal case (as seen in Figure 6). Solid lines correspond to spectra at zero field, while dashed lines represent those under a high electric field of 200 kV/cm. In the nominal case (orange and blue curves), the absorption peak lies near $2.8\mu\text{m}$ at zero field and redshifts to approximately $3.2\mu\text{m}$ under the applied field, with a noticeable reduction in amplitude due to reduced oscillator strength. When parameters are increased by $+15\%$ (green and yellow), the peaks broaden and shift slightly further, particularly under applied field, where the redshift approaches $3.5\mu\text{m}$.

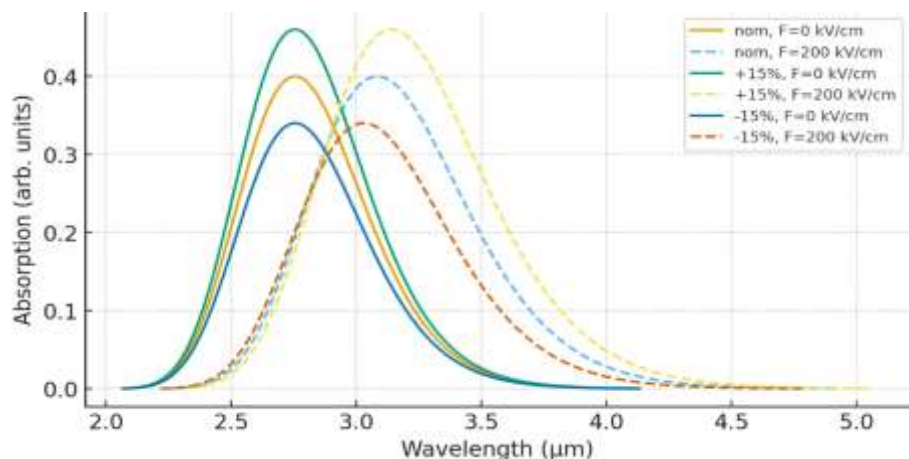


Figure 6: Monte-Carlo sensitivity

Conversely, for -15% variation (brown and red), the peaks move closer to the short-wavelength side, and absorption amplitudes decrease further, especially under high field. This spread in peak positions and intensities highlights the inherent variability expected in real fabricated structures. Importantly, while the qualitative QCSE behavior—redshift with field and reduced amplitude—is preserved across all cases, the degree of tunability and absorption efficiency depends strongly on parameter tolerances. Thus, sensitivity analysis underscores the importance of tight control over material growth and device fabrication to achieve predictable and optimized performance.

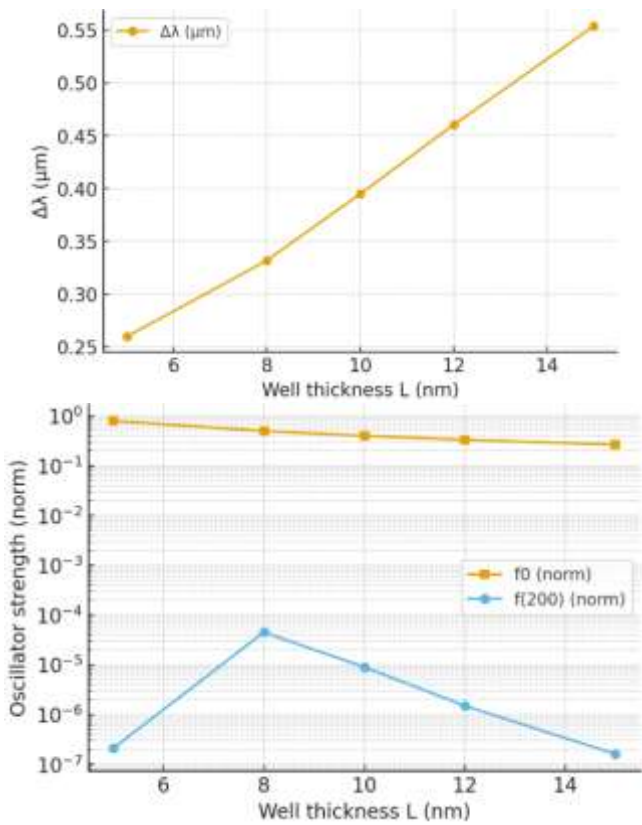
3.4 Comparison Table

The comparison table 2 summarizes the dependence of QCSE parameters on quantum well thickness. As thickness L increases from 5 to 15 nm, both permanent dipole moment and polarizability rise steadily, reflecting stronger electron–hole separation and higher field sensitivity. Correspondingly, the Stark-induced wavelength shift ($\Delta\lambda$) grows from about $0.26\ \mu\text{m}$ at 5 nm to over $0.55\ \mu\text{m}$ at 15 nm, demonstrating greater tunability in thicker wells. At the same time, oscillator strength at zero field (f_0) decreases with thickness, dropping from 0.8 to 0.27, indicating weaker optical transitions. The field-induced decay in oscillator strength at 200 kV/cm is also more severe for thinner wells, nearly vanishing in the 5 nm case. Exciton lifetime, controlled by a parameter η , increases with both thickness and applied field, rising from $\sim 3.3\ \text{ns}$ at 5 nm to $\sim 7\ \text{ns}$ at 15 nm. These results highlight the fundamental trade-off between spectral tunability and absorption efficiency.

Table 2: Comparison table of parameters

L (nm)	Dipole	Polarizability	f_0 (norm)	η	λ (0) (μm)	λ (200) (μm)	$\Delta\lambda$ (μm)	F (200)	Lifetime (200) (ns)
5	0.0666 67	0.000267	0.8	0.0033 33	2.48 06	2.74 04	0.25 98	2.1e- 07	3.3333

8	0.1066 67	0.000427	0.5	0.0053 33	2.65 60	2.98 79	0.33 19	0.0000 45	5.1333
10	0.1333 33	0.000533	0.4	0.0066 67	2.77 24	3.16 75	0.39 51	9.0e- 06	5.6667
12	0.1600 00	0.000640	0.3333 33	0.0080 00	2.88 99	3.35 03	0.46 04	1.5e- 06	6.2000
15	0.2000 00	0.000800	0.2666 67	0.0100 00	3.09 46	3.64 86	0.55 40	1.6e- 07	7.0000



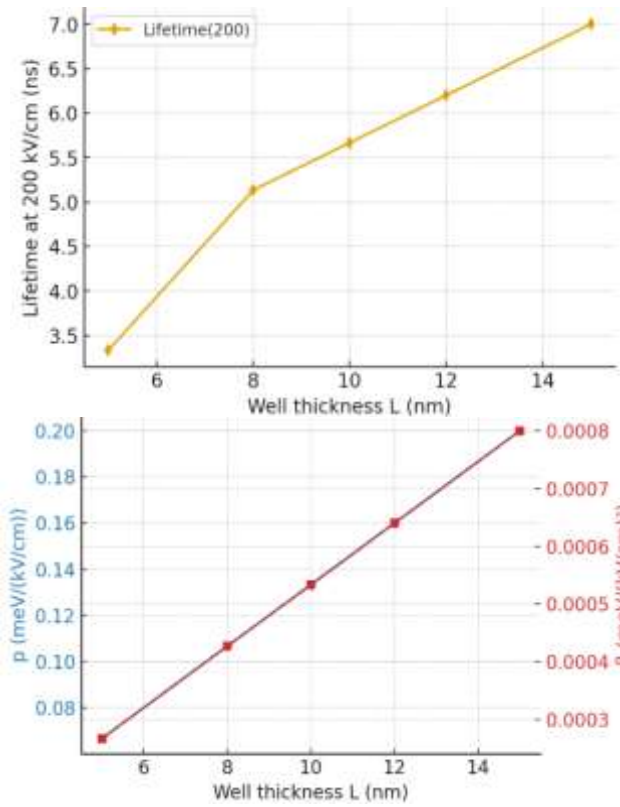


Figure 7: Comparison graph based on parameters

4. Conclusion

In conclusion, this work systematically explored the QCSE in type-II InAs/GaSb multiple quantum wells (MQWs) to evaluate their suitability for tunable mid-infrared photonic devices. By combining theoretical modeling, simulations, and sensitivity analysis, the study established clear correlations between well thickness, applied electric field, and resulting optical properties. The results confirm that thicker wells exhibit stronger dipole moments and polarizabilities, leading to larger Stark-induced redshifts. For instance, the wavelength shift ($\Delta\lambda$) increases from $\sim 0.26 \mu\text{m}$ at 5 nm to $\sim 0.55 \mu\text{m}$ at 15 nm under 200 kV/cm, while the contour analysis indicates tuning ranges up to $\sim 0.7 \mu\text{m}$. However, this enhanced tunability comes at the cost of reduced oscillator strength, which decreases from 0.8 at 5 nm to 0.27 at 15 nm, and further declines under high field. At the same time, exciton lifetimes extend significantly, from ~ 3.3 ns at 5 nm to ~ 7.0 ns at 15 nm, favoring applications requiring longer coherence. Monte-Carlo sensitivity analysis further highlighted the robustness of QCSE behavior while underlining the need for tight control over growth parameters to minimize variability. Overall, these findings demonstrate that a careful trade-off between tunability and efficiency is essential, providing a design roadmap for optimized modulators, detectors, and reconfigurable photonic devices.

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