Strong Light-Matter Interactions for Intersubband Transition in a Flexible Single Quantum Well Structure

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Abstract: We demonstrate ultrastrong coupling between intersubband transitions in single semiconductor quantum well and resonant modes of photonic nanocavities implemented on both rigid and flexible substrates. The Rabi splitting reaches 27% of the intersubband transition frequency.

1. Introduction

Strong light-matter interactions involving intersubband transition (IST) in semiconductor quantum well (QW) can lead to faster IST radiative processes over nonradiative decay mechanisms, which have various pertinent device applications and hence attracted much interest in recent years [1]. The most effective way to achieve strong and even ultrastrong coupling for ISTs in QWs is through enclosing the QWs in a photonic nanocavity which confines electromagnetic fields in deep subwavelength dimensions. Although the coupling strength is in general larger when employing multiple QWs (MQW), the growth of MQW is more difficult and costlier than growing a single QW (SQW). In addition, achieving strong coupling of IST in a SQW may significantly benefit several IST-based device applications such as QW infrared photodetector (QWIP). In addition, compared to MQW structures, it is much easier to realize flexible SQW structures integrated on flexible substrates, since bending induces more strain for thicker semiconductor structures. However, it is significantly more challenging to achieve the same coupling strength in a SQW system than in a MQW system. Recently, strong coupling involving the IST in a heavily doped SQW was demonstrated [2], whereas the ultrastrong coupling regime for IST in a SQW has not been reached yet. In this work, we experimentally achieved ultrastrong coupling of IST in a GaAs SQW with a Rabi splitting ($2\Omega_R$) reaching 27% of the IST frequency. Also, we investigated InGaAs SQW which supports two ISTs, and both ISTs achieved strong coupling with the nanocavity resonance mode. Furthermore, we demonstrated that such strong light-matter interactions can be achieved in flexible SQW structures implemented on bendable substrates made of PDMS.

2. Structure Design and FDTD Simulation

To establish strong light-IST interaction, we employed nanocavity designs of the patch antenna type consisting of top metal strip array and a bottom metal ground plane. In our SQW heterostructure designs, the thin SQW layer (GaAs or InGaAs) is sandwiched by barrier layers (AlGaAs or AlInAs) and cap layers (GaAs or InGaAs). The cap layers prevent the barrier layers from oxidation and reduce the influence of surface trap states. The schematic of the designed structures is illustrated in Fig. 1a. The reflection spectra and the electromagnetic field distributions of the investigated structures were simulated using Lumerical FDTD. The simulated electric field distribution shown in Fig. 1b reveals the large electromagnetic field confinement and enhancement inside the SQW layer.

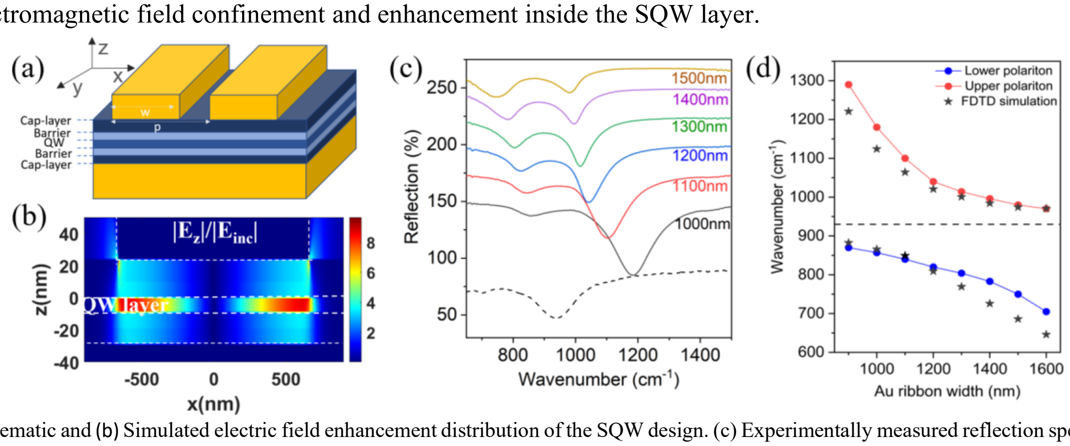

Figure 1 (a) Schematic and (b) Simulated electric field enhancement distribution of the SQW design. (c) Experimentally measured reflection spectra of patch antenna arrays (solid lines) where the dashed line shows IST absorption spectrum and (d) dispersion of IST polaritons extracted from (c).

3. Sample Fabrication

We have fabricated the designed SQW structures on both rigid (e.g., glass) and flexible substrate (e.g., PDMS). The SQW structures on glass substrate were fabricated using a standard nanofabrication process where Ti/Au ground plane were deposited on the SQW surface. The sample is then bonded onto another glass substrate using epoxy with subsequent removal of the semiconductor substrate using mechanical lapping followed by chemical etching. The designed metal strip arrays were then patterned on the sample surface using electron-beam lithography, followed by metal deposition and lift-off. On the other hand, to fabricate flexible SQW structures on PDMS substrate, first we have patterned metal strip arrays on the sample surface and then we flipped the sample and attached it with wax on a glass substrate where we removed the semiconductor substrate as usual. Subsequently, we deposited the metal ground plane, dipped the sample inside uncured PDMS and let the PDMS to be cured at room temperature for 2 days. After PDMS curing, we immerse the sample in acetone to remove the glass substrate by dissolving the wax layer. This overall fabrication process is depicted in Fig. 2a.

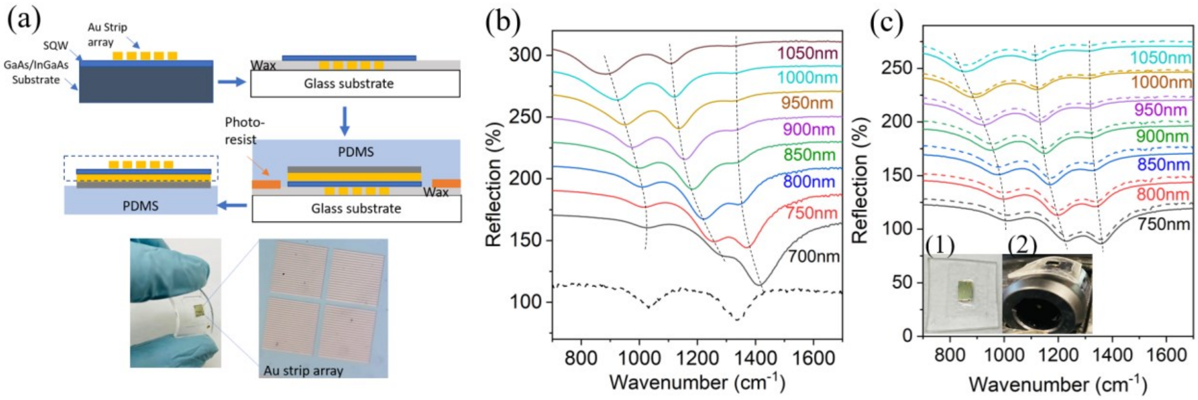

Figure 2 (a) Fabrication steps for SQW-based patch antennas on flexible PDMS substrate. Measured reflection spectra of patch antenna arrays containing InGaAs SQW with various Au strip widths on (b) glass substrate (the dashed line shows absorption spectrum of two ISTs) and (c) PDMS substrate at flat (solid lines) and bended (dashed lines) conditions. Inset of (c) shows the (1) flat and (2) bended sample images.

4. Experimental Results

We studied two different III-V semiconductor SQW structures, i.e., a $GaAs/Al_{0.3}Ga_{0.7}As$ SQW (two-level system) and an $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ SQW (three-level system). The designed nominal sheet carrier density in the GaAs SQW is 4.4×10^{12} cm^{-2} and in the InGaAs SQW is 6.9×10^{12} cm^{-2}, which are much lower than those of previous work [2]. The single IST in the GaAs SQW was observed at 930cm^{-1} and two ISTs in the InGaAs SQW were found at 1030 cm^{-1} and 1335 cm^{-1}. The reflection spectra of the fabricated patch antenna structures with different gold strip widths (50% duty cycle) for the GaAs SQW were measured by FTIR at room temperature, shown in Fig. 1c. From the spectra, we can see that the designed patch antenna nanocavities were effective for achieving strong light-IST interactions, which led to the formation of two IST polariton modes. The frequencies of the IST polaritons were extracted to yield the polariton dispersion shown in Fig. 1d where variation of the frequency difference between the upper and lower IST polaritons can be clearly observed. We achieved ultrastrong coupling for the IST in the GaAs SQW with a Rabi splitting measured to be 213cm^{-1} (6.4THz), which is 27% of the IST frequency (~24THz), much higher compared to that achieved in previous work on strong light-IST interactions in SQW structures [2].

The reflection spectra of the patch antenna structures based on the InGaAs SQW were measured and plotted in Fig. 2. Figure 2b shows the spectra of patch antenna structures on rigid glass substrate and Fig. 2c shows the spectra of the same structures on flexible PDMS substrate. For this InGaAs SQW, the nanocavity resonance strongly coupled to both the first order IST with a Rabi splitting of 180cm^{-1} (5.4THz) and the second order IST with a Rabi splitting of 126cm^{-1} (3.8THz). The structures on flexible substrate show similar spectral characteristics as the structures on rigid substrate. In addition, bending of the flexible substrate does not cause any significant spectral change (see Fig. 2c).

5. Conclusion

In summary, we have experimentally observed and systematically investigated the ultrastrong coupling between nanophotonic resonators and ISTs in SQWs based on two different material systems (GaAs/AlGaAs and InGaAs/AlInAs). The Rabi splitting reached 27% of the IST frequency for the GaAs SQW structures, which is the highest coupling strength achieved with SQW structures in MIR region. Strong coupling was also achieved for the second order IST in the InGaAs SQW structures. We also implemented such SQW structures on a flexible substrate, which exhibited similar coupling strengths as those on a rigid substrate. The demonstrated flexible SQW-based IST polaritonic systems can be employed for various device applications such as flexible photodetectors and light sources.
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References

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