

Intersubband Cavity Polaritons in Single Quantum Well Systems on Flexible Substrate

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Abstract—We demonstrate strong and ultrastrong coupling between intersubband transitions in single semiconductor quantum well systems and resonant modes of photonic nanocavities implemented on flexible substrates. The spectral characteristics of the observed intersubband cavity polaritons exhibit robustness to large bending of the flexible substrates.

Keywords—intersubband transition, cavity polariton, quantum well, soft photonics

I. INTRODUCTION

Intersubband transition (IST) in quantum well (QW) is the foundation of several key device technologies in the mid-infrared and terahertz spectral regions, including quantum cascade lasers and quantum infrared photodetectors. However, ISTs in QWs are subject to various ultrafast non-radiative carrier scattering processes (e.g., optical phonon and interface roughness scattering), making the intrinsic radiative transition efficiency of ISTs relatively low. Establishing strong light-matter interactions involving ISTs and cavity photons can lead to much faster IST radiative processes over the nonradiative decay mechanisms, which have a variety of device applications and hence attracted much interest in recent years [1]. One of the most effective ways to achieve strong or even ultrastrong coupling for ISTs in QWs is to enclose the QWs in a photonic cavity with high field confinement and enhancement. Several groups have demonstrated strong and ultrastrong coupling between cavity photons and ISTs in multiple QW (MQW) structures implemented on rigid semiconductor substrates. Although the coupling strength is in general larger when employing more QWs, realizing strong or ultrastrong coupling for ISTs in single QW (SQW) structures is nevertheless highly desired [2], as it would lead to several key advantages. For example, it is straightforward to control the IST transition strength in a SQW by tuning the carrier density in the SQW via field effect, which would be challenging or impractical for MQW structures. In addition, flexible SQW structures realized on flexible substrates can be more robust than the MQW counterparts, as bending induces more strain in thicker heterostructures. However, it is much more challenging to achieve the same coupling strength in a SQW-based system than in a MQW-based system. In this work, we experimentally demonstrated for the first time ultrastrong coupling between cavity photons and ISTs in SQWs. Furthermore, also for the first time, we realized such IST cavity polariton systems on soft and flexible substrates and observed that the characteristics of the IST cavity polaritons are robust to large bending of the flexible substrates [3].

II. DEVICE DESIGN AND SIMULATION

We designed two semiconductor SQW heterostructures, each of which consists of a SQW layer (GaAs or InGaAs) sandwiched by the barrier layers (AlGaAs or AlInAs) and cap layers (GaAs or InGaAs). These structures were grown using molecular beam epitaxy (MBE) on GaAs and InP substrates, respectively. The cap layers were employed to prevent the barrier layers from oxidation and reduce the influence of surface trap states. To establish strong light-IST interaction, we employed the patch antenna type nanocavity design illustrated in Fig. 1(a), which consists of a top Au nanostrip and a bottom Au ground plane sandwiching the SQW heterostructure. We simulated the spectral responses and field distributions of the nanocavity arrays with different geometrical parameters using Lumerical FDTD. Fig. 1(b) reveals the large electromagnetic field confinement and enhancement inside the SQW. In addition, the reflection spectra exhibit the typical characteristics of cavity polariton modes. Ultrastrong coupling can be achieved when the cavity height is about 50 nm or less.

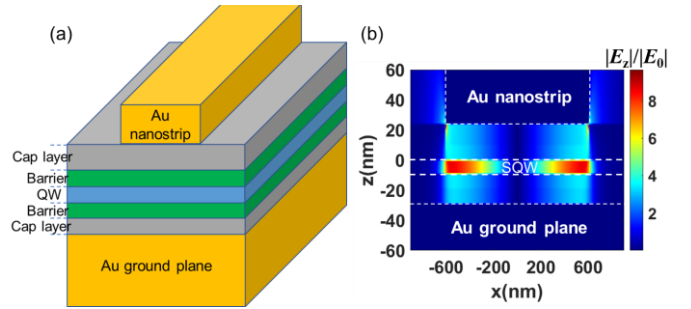


Fig. 1. (a) Schematic illustration of the patch antenna type nanocavity design. (b) Simulated electric field profile in the nanocavity at the upper IST cavity polariton mode showing high field confinement/enhancement in the SQW.

III. DEVICE FABRICATION

We fabricated the designed SQW-based nanocavity arrays on both rigid (e.g., glass) and flexible (e.g., PDMS) substrates. The SQW structures on glass substrate were fabricated using a conventional process [3]. First, Ti/Au ground plane was deposited on the SQW surface. The sample was then bonded onto another glass substrate using epoxy, followed by the subsequent removal of the semiconductor substrate via mechanical lapping and chemical etching. The designed Au nanostrip arrays were then patterned on the sample surface using electron-beam lithography, followed by metal deposition and lift-off. On the other hand, we developed an alternative process

to fabricate flexible SQW-based structures on PDMS substrate, which is illustrated in Fig. 2. We first patterned the Au nanostrip arrays on the sample surface, and then flipped the sample to secure it with wax on a glass substrate. The semiconductor substrate was subsequently removed. We then deposited the Au ground plane, dipped the sample into uncured PDMS and let the PDMS to be cured at room temperature for 2 days. After the PDMS was cured, we immersed the sample in acetone to dissolve the wax layer and hence release the glass substrate, leaving the fabricated SQW-based nanocavity arrays on the flexible PDMS substrate which can be bent to a large extent.

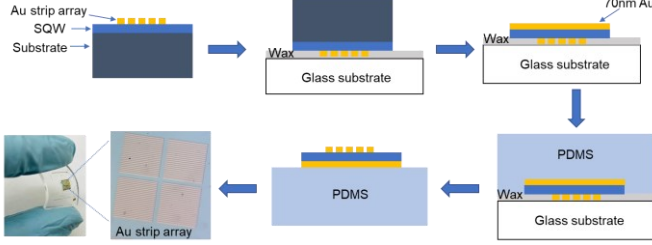


Fig. 2. Schematics for the fabrication process of SQW-based IST cavity polariton devices on flexible PDMS substrate. The image on the lower left corner shows a fabricated device being held and bent to a relatively large extent.

IV. EXPERIMENTAL RESULTS

The two SQW structures studied exhibit different ISTs. The GaAs/Al_{0.3}Ga_{0.7}As SQW has a single IST between two subbands, whereas the In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As SQW has three subbands and hence two ISTs. The nominal sheet carrier density in the GaAs SQW is $4.4 \times 10^{12} \text{ cm}^{-2}$ and in the

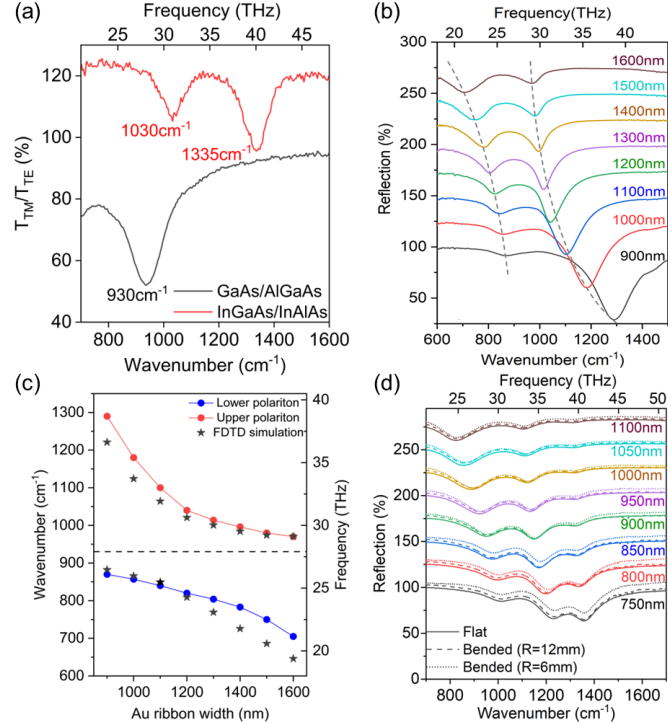


Fig. 3. (a) Measured IST absorption of the two SQW structures. (b) Reflection spectra of the GaAs SQW-based nanocavity arrays with different Au nanostrip widths. (c) Comparison between measured and simulated GaAs SQW-based IST cavity polariton dispersions. (d) Reflection spectra of the InGaAs SQW-based nanocavity arrays on flexible PDMS substrate bent to different extent.

InGaAs SQW is $6.9 \times 10^{12} \text{ cm}^{-2}$. The single IST in the GaAs SQW was observed at 930 cm^{-1} and the two ISTs in the InGaAs SQW were at 1030 cm^{-1} and 1335 cm^{-1} , respectively, as shown in Fig. 3(a). The reflection spectra of the GaAs SQW-based nanocavity arrays with different Au nanostrip widths are shown in Fig. 3(b). The two reflection dips in each spectrum correspond to the two IST cavity polariton modes, which exhibit the anti-crossing characteristics as the Au nanostrip width and hence the nanocavity resonance vary across the IST frequency. The frequencies of the IST cavity polaritons were extracted to yield the polariton dispersion shown in Fig. 1(c) which shows good agreement with the simulated results. The Rabi splitting is found to be 220 cm^{-1} ($\sim 6.6 \text{ THz}$), which is about 24% of the IST frequency and therefore within the ultrastrong coupling regime. To the best of our knowledge, this is the first demonstration of ultrastrong light-IST interaction in SQW-based structures. The reflection spectra of the InGaAs SQW-based nanocavity arrays on a flexible PDMS substrate bent to different extent are shown in Fig. 3(d). Three reflection dips were observed in each spectrum, which is the result of the strong interactions between two ISTs and the nanocavity resonance. The Rabi splitting associated with the first-order IST is 198 cm^{-1} ($\sim 5.9 \text{ THz}$), which is $\sim 19\%$ of the IST frequency and hence at the cusp of the ultrastrong coupling regime. The strong coupling to the second-order IST resulted in a Rabi splitting of 126 cm^{-1} ($\sim 3.8 \text{ THz}$). Furthermore, as can be clearly seen in Fig. 3(d), the spectral characteristics of the observed IST cavity polaritons exhibit robustness to large bending of the flexible PDMS substrate [3].

V. CONCLUSION

We have experimentally demonstrated and systematically investigated the ultrastrong coupling between the resonance of nanophotonic cavities and ISTs in SQWs based on two different material systems (GaAs/AlGaAs and InGaAs/AlInAs). The Rabi splitting reached 24% of the IST frequency for the GaAs SQW-based structures, which corresponds to the largest coupling strength achieved with SQW systems to date. Strong coupling was also observed for the second-order IST in the InGaAs SQW-based structures. Furthermore, we successfully realized for the first time QW-based IST cavity polariton systems on flexible substrate, which exhibited similar coupling strengths as those on rigid substrate and robustness to large substrate deformations. Such flexible SQW-based IST cavity polariton systems may enable a variety of new device applications such as flexible photodetectors and light sources.

ACKNOWLEDGMENT

This work was in part supported by the NSF (ECCS-1847203) and the Center for Integrated Nanotechnologies at Sandia National Laboratories.

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