HTML ABSTRACT + LINKS

Theory of Raman Lasing due to Coupled Intersubband Plasmon-Phonon Modes in Asymmetric Coupled Double Quantum Wells

S. M. Maung and S. Katayama

School of Materials Science, Japan Advanced Institute of Science and Technology, 1-1 Asahidai, Tatsunokuchi, Ishikawa 923-1292, Japan

Abstract. A theory of Raman laser gain due to coupled intersubband (ISB) plasmon-optical phonon modes in asymmetric coupled double quantum wells (ACDQWs) is presented. Based on the charge-density-excitations (CDE) mechanism, we take into account the electron-electron and electron-phonon (confined LO phonon and interface (IF) phonons) interactions in the scattering cross-section. For $Al_{0.35}Ga_{0.65}As/GaAs$ ACDQWs the calculated coupled mode energies which are responsible for the lasing Stokes emission are well consistent with recent experiments.

INTRODUCTION

Recently, optically pumped unipolar three-level intersubband Raman laser (IRL) has been realized [1] for mid-infrared radiation in modulation-doped GaAs/ $Al_{0.35}Ga_{0.65}As$ asymmetric coupled double quantum wells (ACDQWs). By using various samples with CO_2 laser, a new evidence associated with coupled intersubband (ISB) plasmon-optical phonon modes has been found [2]. It has been clarified theoretically based on the charge-density-excitation (CDE) mechanism that the coupled ISB plasmon-LO phonon mode with the largest Raman cross-section dominates the lasing action [3]. In this paper we further develop a theory of Raman lasing due to coupled ISB plasmon-phonon modes by considering confined nature of LO phonon and including the interface (IF) phonons in ACDQWs.

THEORY

The schematic view of IRL is shown in Fig. 1a. In our CDE mechanism Stokes emission can be understood by adopting the 2-step scattering process as illustrated in Fig. 1b [3] so that the light scattering process contains the ISB excitations (1→2). Further, owing to electron-electron and electron-phonon interactions, the ISB excitation energy is shifted from E_{21} ($=E_2$-E_1) to the coupled ISB plasmon-phonon mode energy. The Raman laser gain (G_R) in IRL has been given in terms of the scattering cross-section ($d^2\sigma/d\omega\, d\Omega$), subband populations ($N_{1(2)}$) and pump intensity ($I_{pump}$) in ref. 3 as

$$G_R \propto (d^2\sigma / d\omega d\Omega)(N_1 - N_2) I_{pump}. \quad (1)$$

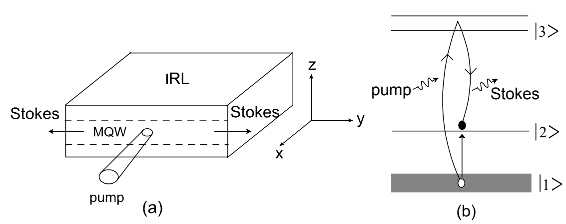

FIGURE 1. (a) Schematic view of IRL device, (b) 2-step CDE Raman scattering process.

Within the RPA we obtain the scattering cross-section with use of dynamical susceptibility function χ_{11} related to the virtual (1,2)→(2,1) transitions as

$$\frac{d^2\sigma}{d\omega d\Omega} = -\frac{r_0^2\hbar}{\pi}\left(\frac{\omega_s}{\omega_i}\right)|R|^2 (n(\omega)+1)\,\mathrm{Im}\,\chi_{11}(q,\omega), \quad (2)$$

where r_0 is the classical radius of an electron, R is the intersubband Raman tensor and $n(\omega)$ is the Bose-Einstein factor. Poles of $\chi_{11} = \chi^0 / [1 - V_{11}^{\mathrm{eff}} \chi^0]$ are

CP772, *Physics of Semiconductors: 27th International Conference on the Physics of Semiconductors,* edited by José Menéndez and Chris G. Van de Walle
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determined by the linear response function χ^0 and the effective electron-electron interaction V_{11}^{eff} given by

$$V_{11}^{\text{eff}} = \frac{4\pi\, e^2 L_{11}}{\varepsilon_\infty} + \sum_\nu \frac{2\hbar\omega_{q,\nu}\left|V_{q,\nu}\right|^2}{\hbar^2(\omega^2 - \omega_{q,\nu}^2)}, \qquad (3)$$

where L_{11} and $V_{q,\nu}$ denote the matrix element of Coulomb interaction and the electron-phonon coupling strength for mode ν.

CALCULATIONS AND DISCUSSION

To evaluate the scattering cross-section of GaAs/ $Al_{0.35}Ga_{0.65}As$ ACDQWs with $N_s = 3\times10^{11}$ cm^{-2}, we calculate the subband states as well as $V_{q,\nu}$ and $\omega_{q,\nu}$. Figure 2 shows the calculated cross-section for three ACDQWs. It is seen in Figs. 2a and 2b that the peak

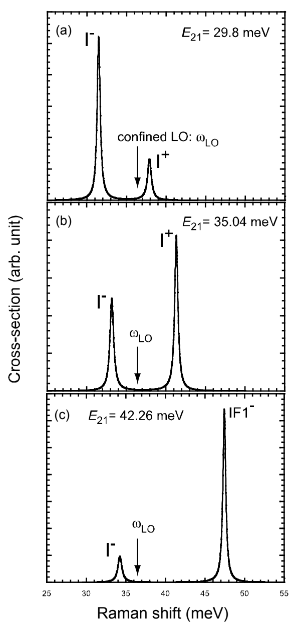

FIGURE 2. Calculated scattering cross-section for three ACDQWs samples. In (a) $E_{21}<\hbar\omega_{LO}$ (confined GaAs), (b) $\hbar\omega_{LO}\sim E_{21}<\hbar\omega_{IF1}$, and (c) $\hbar\omega_{LO} <E_{21}< \hbar\omega_{IF1}$.

(I^-) corresponding to lower coupled ISB plasmon-confined LO phonon mode dominates the cross-section for $E_{21}<\hbar\omega_{LO}$, while the upper peak (I^+) becomes dominant in spectrum for $\hbar\omega_{LO}\sim E_{21}<\hbar\omega_{IF1}$. More important fact is seen in Fig. 2c in which the peak ($IF1^-$) corresponding to coupled ISB plasmon-IF1 phonon mode has the strongest intensity for $\hbar\omega_{LO} <E_{21}< \hbar\omega_{IF1}$. These results can be explained by the two factors appearing in V_{11}^{eff} of Eq. (3). The first one is the resonance between E_{21} and $\omega_{q,\nu}$ and the second is the coupling strength $V_{q,\nu}$. To compare with the IRL experiments [2], we have calculated the density of Stokes photons associated with coupled modes using laser rate equations [3].

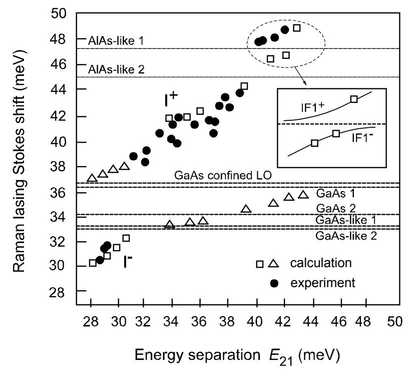

FIGURE 3. Raman lasing Stokes shift versus E_{21}. All calculated phonon mode-energies for wave vector qa = 0.016 (a being the wide barrier width) in ACDQWs samples are also shown.

In Fig. 3 we plot the calculated Raman Stokes shifts (coupled mode energies) versus E_{21} by solving the laser rate equations for several ACDQWs. The horizontal dashed lines show the calculated six IF phonon modes and confined GaAs LO phonon mode. The open squares and open triangles indicate the calculated Raman lasing Stokes shifts and non-lasing Stokes shifts corresponding to coupled ISB plasmon-phonon modes (I^-, I^+, $IF1^-$ and $IF1^+$). The Solid circles represent the experimental Raman lasing Stokes shifts. Calculated coupled mode energies are well consistent with the experimental results [2].

In conclusion, we have developed a theory of Raman laser in ACDQWs, based on the differential scattering cross-section due to the coupled ISB plasmon-optical phonon modes. The theory can predict the correct lasing mode frequencies observed in recent experiments.

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