

Multi-color emission wavelength switching in a strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ quantum well

N. Yasuhara¹ and S. Fukatsu^{1,2}

¹Graduate School of Arts and Sciences, The University of Tokyo
Komaba, Meguro, Tokyo 153-8902, Japan

²PRESTO, Japan Science and Technology Agency (JST)
Kawaguchi, Saitama 332-0012, Japan

Abstract- Three-color voltage-controlled emission wavelength switching (VCEWS) is demonstrated in a strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ triple quantum well, paving a way toward a Si-based, monolithic multi-color-selectable light emitting diode.

INTRODUCTION

Capability of tuning the emission wavelength of an incoherent semiconductor light emitter promises a broad range of applications. Additional requirement in many applications is the single-chip operation. To this end, it is imperative to put under control the active regions that allow different emission wavelengths. One possible way is to directly control the carrier densities in the two or more active regions. This may be easier if one is able to do it with respect to *only one* type of the carriers simply by applying bias voltages: whichever is small in number between the two types of carriers controls the emission intensity as it is proportional to the product of the concentrations of the electrons and holes.

Recently, we have demonstrated two-color voltage-controlled emission wavelength switching (VCEWS) of *photoluminescence* (PL) in a strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ double quantum well (DQW) by modulating electron densities through longitudinal electric fields across the DQW [1]. This works out because of the shallow confinement of the electrons in a type-II lineup, which characterizes the strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ QWs. This scheme has been extended to *electroluminescence* (EL) by utilizing impact ionization that is easy to occur in a reverse-biased Si and SiGe. We have been successful in two-wavelength VCEWS in a strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ DQW and hence a wavelength switchable strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ -QW light emitting diode (LED) was achieved.

In this report, we demonstrate successful three-color VCEWS in PL mode in a strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ triple QW (TQW). In contrast, the number of available wavelengths in VCEWS in EL mode is limited to two in one dimension since the direction of current corresponds to one wavelength.

EXPERIMENTAL

Sample was a nominally-undoped pseudomorphic $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ TQW grown on on-axis p-type Si(001). The well

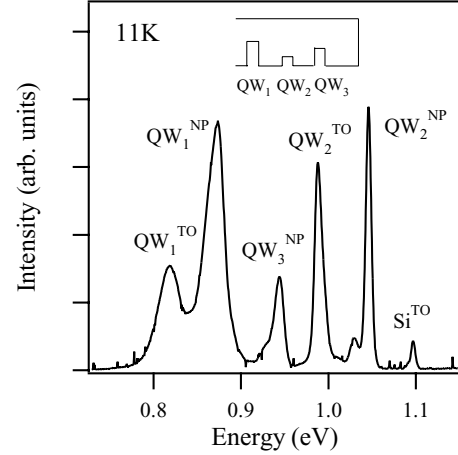


Fig. 1. 11-K PL spectrum of a strained $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ TQW with $x = 0.64$, $L_z = 32$ Å (QW_1), $x = 0.15$, $L_z = 34$ Å (QW_2) and $x = 0.30$, $L_z = 126$ Å (QW_3). NP and TO refer to no-phonon transition and its phonon replica, respectively. Inset is a schematic drawing of potential line-up.

widths and Ge contents are $L_z^{(1)}=32\text{\AA}$, $x=0.64$ for the buried well (QW_1), $L_z^{(2)}=34\text{\AA}$, $x=0.15$ for the middle well (QW_2) and $L_z^{(3)}=126\text{\AA}$, $x=0.30$ for the near-surface well (QW_3), respectively. The two adjacent wells are separated by a $0.8\text{-}\mu\text{m}$ Si. Fig. 1 shows the typical cw PL spectrum from the TQW. The PL emissions of the three QWs are well resolved. Longitudinal electric field was applied through aluminum electrodes deposited on both wafer faces.

RESULTS AND DISCUSSION

Figure 2 (a) shows the PL spectra at 70 K as a function of bias voltage. It is visible that the peak intensities of the QW_1 and QW_3 switch over at a reasonable extinction ratio as the bias voltage is varied. This is explained simply as due to the redistribution of the electrons under longitudinal electric field: at a positive surface bias, more electrons are attracted toward the near-surface QW_3 than the buried QW_1 and vice versa. A plot of the normalized peak intensities of no-phonon PL from the three QWs is shown in Fig. 2 (b) as a function of bias voltage. The PL intensity variation of the QW_2 with bias voltage is in between the QW_1 and QW_3 since the electrons are redistributed between QW_1 and QW_3 depending on the electric field. Thus nearly successful three-color VCEWS is

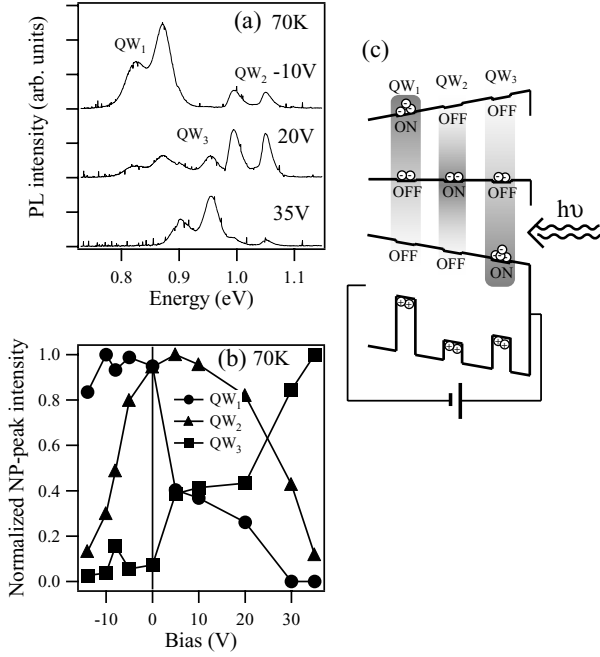


Fig. 2 PL spectra taken at 70 K (a) and a plot of the normalized peak intensities of the no-phonon PL (b) as a function of bias voltage. (c) Diagrammatic representation of carrier distribution under longitudinal electric fields which enable the three-color VCEWS in PL mode.

achieved in the cw mode although spectral dominance of the QW₂ remains as low as 50% in terms of extinction ratio in our particular sample.

Figure 3 shows 5.6-K EL spectra as a function of current. The spectral dominance switch between QW₁ and QW₃ is observed in EL at a good extinction ratio. However, EL of QW₂ is not observed regardless of the bias voltages. When the surface is negatively biased (forward bias), only EL from QW₁ was observed while EL from QW₃ is dominant under the surface positive bias (reverse bias). Note that under the reverse bias, the dark currents are higher because of impact ionization. The clear spectral dominance switch between the surface QW (QW₃) and substrate QW (QW₁), and the absence of EL of the middle QW (QW₂) indicate that the holes and the electrons tend to the QW on the positive electrode side (QW₁ or QW₃). This tendency can be explained in terms of field drift of the electrons that are otherwise subject to weak-confinement to the QWs in the presence of the space charge of the quantum-confined holes, as shown fig. 3 (c). 1) The loosely bound electrons in the two upstream QWs with respect to the electron current tend to the downstream QW upon application of bias voltage [2] while the quantum-confined holes continue to stay in the QWs. 2) The upstream QW with respect to the hole current captures more holes than the other two downstream QWs since hole collection efficiency is high (~80 %).

Three-color VCEWS in PL mode is allowed by utilizing two degrees of freedom, which modulate carrier distribution: the penetration depth of excitation light and the electric field. In the case of VCEWS in EL mode, however, electric field

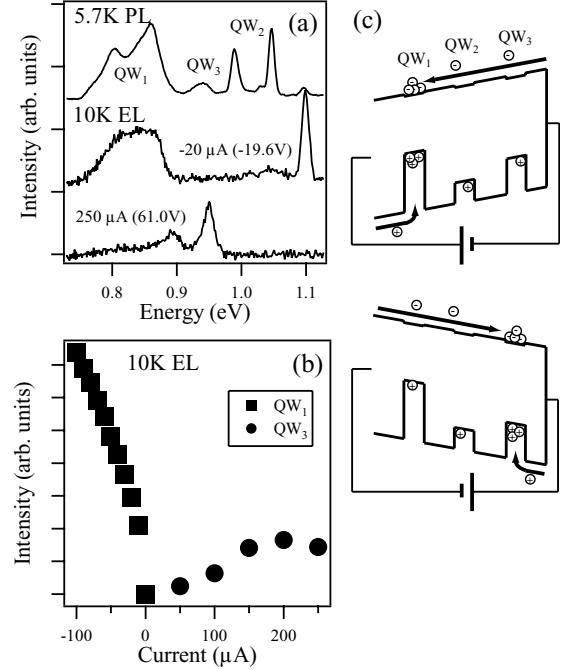


Fig. 3 EL spectra taken at 10 K (a) and a plot of EL intensities as a function of current intensity (b). (c) Diagrammatic representation of carrier drift and redistribution under longitudinal electric fields, showing the principle of VCEWS in EL mode.

turns out to be the only factor that controls the carrier redistribution. Introduction of another means that can directly modulate the electron distribution will allow multi-color VCEWS. Study is now in progress.

CONCLUSION

Three-color voltage-controlled emission wavelength switching (VCEWS) was demonstrated in PL mode in a strained Si_{1-x}Ge_x/Si triple quantum well by utilizing redistribution of the electrons under electric field in a type-II lineup. In EL mode, VCEWS was limited to two-color.

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