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An Effect of Fabrication Damage on Carrier-Dynamics in MQW Narrow Wires

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The optical nonlinearity of excitons in quantum wells is attractive for new optical device application. Since the exciton absorption recovery time in multiple quantum wells (MQWs) is too slow ($\geq$ 1 ns), we have used surface recombination of excitons by fabricating MQWs to narrow wire structures to reduce recovery time[1)]. Figure 1 shows experimental recovery time dependence on wire width for two different etching yields. With a decrease in etching yield, fabrication damage is expected to increase. For samples shown by open circles in Fig. 1, the recovery time is almost proportional to wire width. While, for samples shown by closed circles, where heavier damage is expected, the recovery time decrease is more than the square of wire width. The recovery time should be proportional to the square of wire width when it is limited by diffusion of carriers[2)]. While, the recovery time should be proportional to wire width when it is limited by surface recombination[3,4)]. Therefore, it is impossible to explain this tendency by the diffusion-surface recombination model. In this study, we performed numerical calculation using a simple damage model to clarify how damage affects the wire width dependence.

The time-variation of carrier density n is expressed by the model in which carriers diffuse toward the sidewall and vanish due to surface recombination[3,4)]. In addition to these effects, we considered the effect of damage using the nonradiative recombination rate $1/\tau(x)$ which decays exponentially from the sidewall[5)] as shown in Fig. 2. It is defined as,

$$1/\tau(x) = (1/\tau_0)\,[\exp\{(x - L + d)\,m\} + \exp\{-(x + L - d)\,m\}], \qquad (1)$$

where τ_0 is the lifetime of carriers in "bulk" MQW, 2L is the wire width, d is the distance from the surface to the intersection of $1/\tau(x)$ and $1/\tau_0$, defining the depth of damage layer from sidewall and m is magnitude of the slope. The rate equation is given by,

$$\partial n/\partial t = D\,(\partial^2 n/\partial x^2) - n/\tau(x) - n/\tau_0, \qquad (2)$$

where D is the diffusion coefficient of carriers. The boundary conditions are,

$$\pm D\,(\partial n/\partial x) = -S\,n \qquad (\text{for } x = \pm L), \qquad (3)$$

where S is the surface recombination velocity. We solved Eqs. (1), (2) and (3) numerically by the finite difference method. All calculations were performed for $D = 20\ \mathrm{cm^2/s}$, $S = 5 \times 10^5$ cm/s and $\tau_0 = 5$ ns, according to the previous results[1)].

Figure 3 shows calculated recovery time dependence on wire width by assuming $m/\ln(10) = 0.05\ \mathrm{nm^{-1}}$ ($1/\tau(x)$ changes one order per 20 nm). The recovery time is defined as the full width at the $1/e$ of initial carrier intensity in the time-variation curve. The curves for damaged region d = 0, 60 and 80 nm show linear relationship with wire width, indicating the surface recombination limit. While, the curve for d = 120 nm has a recovery time which decreases more drastically. Thus, the experimental tendency can be simulated. Figure 4 shows time-variation of carrier density distribution curve for 2L = 500 nm. For d = 80 nm, carriers are distributed in all wire regions. For d = 120 nm, few carriers exist near the sidewalls (shown by shaded portions). This indicates the presence of a "dead layer" in which carriers vanish almost immediately due to damage. In other words, the "effective" wire width is less than the physical width. In fact, it can be shown that the recovery time is almost proportional to the square of the "effective" wire width. Therefore, we conclude that the drastic reduction in recovery time for heavily damaged samples is due to a formation of a "dead layer" near the sidewall.

References

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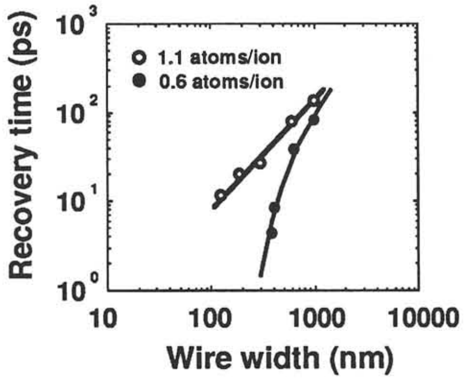

Fig. 1 Experimental recovery time dependence on wire width.

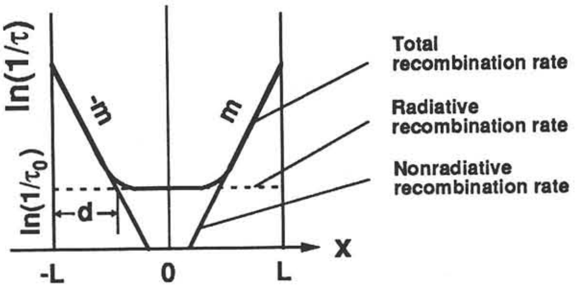

Fig. 2 Numerical calculation model for fabrication damage at wire sidewalls.

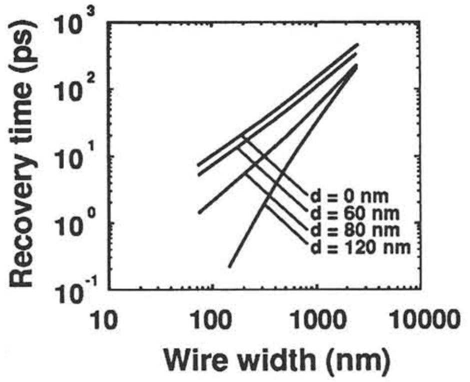

Fig. 3 Calculated recovery time dependence on wire width. All calculations were performed for D = 20 cm^2/s, S = 5 x 10^5 cm/s, τ_0 = 5 ns and m/ln(10) = 0.05 nm^{-1}.

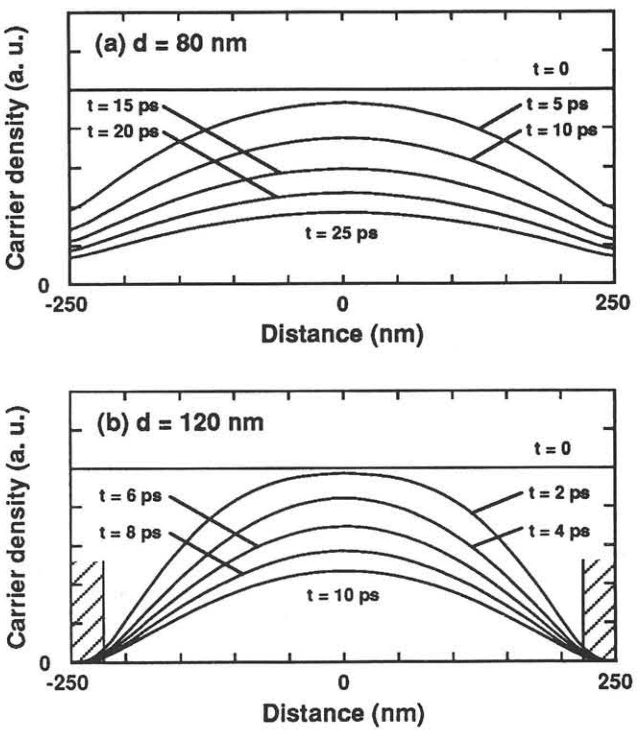

Fig. 4 Time-variation of carrier density distribution curve (2L = 500 nm). Also see Fig. 3 caption.