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Excitation Power Dependent Photoluminescence Characterization and Successful Edge Passivation of Etched InGaAs Quantum Wires Formed by Electron Beam Lithography

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A novel Si Interface Control Layer (Si ICL) based-passivation technique was applied to the air exposed surfaces of InGaAs wires fabricated by EB lithography and wet chemical etching. The effect of passivation was investigated by photoluminescence (PL). The results indicated that the conventional PL characterization method assuming a surface recombination velocity is inadequate. A novel method utilizing the excitation power dependence of PL intensity was introduced. The novel method strongly indicates that the Si ICL technique is powerful for edge passivation of wires.

1. INTRODUCTION

Low-dimensional quantum nanostructures, such as quantum wires and dots, are recently attracting attention as building blocks for next-generation quantum LSIs and optoelectronic devices. The most straightforward practical approach for nanostructure fabrication is combined use of EB lithography and etching. With this approach, however, process-induced surface damage is known to be serious which is manifested by rapid reduction of PL intensity with size reduction. Thus, a suitable surface passivation together with a proper characterization of its effect is a key technological issue for such an approach.

For passivation of compound semiconductor quantum structures, we have recently developed a novel passivation technique using a Si interface control layer (Si ICL) [1)-3)] and successfully applied it to the passivation of GaAs-based near surface quantum wells [4),5)] and InP-based selectively grown quantum wires.[6)]

The purpose of this paper is to apply the Si ICL-based passivation technique to the edges of InP-based InGaAs wires formed by EB lithography and wet chemical etching, and to characterize the effect of passivation by PL measurements. It is shown that the conventional PL characterization method assuming a constant surface recombination velocity, S, and dead layer width, W_{dead}, is inadequate. A novel excitation power dependent PL characterization method taking account of excitation power dependence of the surface recombination velocity is developed and applied in this study for characterization of the wire quality. The result shows the Si ICL technique is found to be extremely powerful for edge passivation of quantum structures formed by EB lithography and etching.

2. EXPERIMENTAL

The structures of the wire samples with and without a Si ICL-based passivation structure are shown in Fig.1. The sequence of sample preparation was as follows. First,

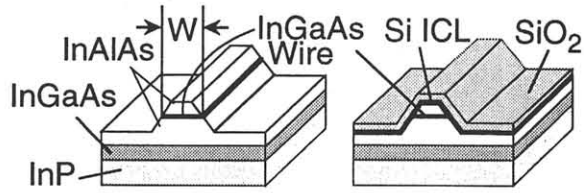


Fig.1 Sample Structures.

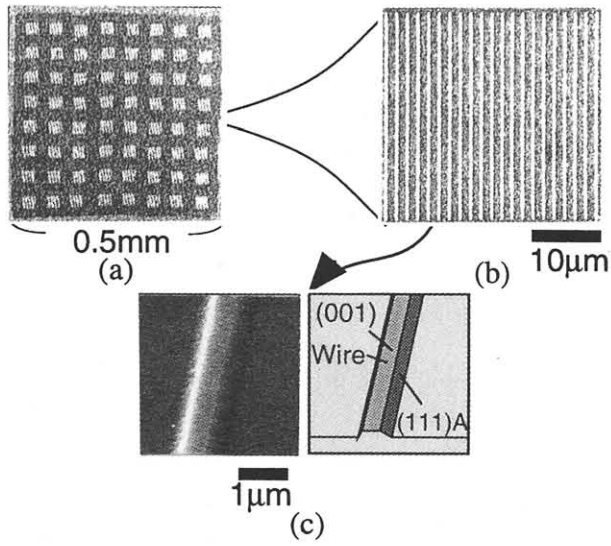


Fig.2 SEM micrographs of wire arrays..

$In_{0.53}Ga_{0.47}As$ quantum well (QW) wafers were grown by molecular beam epitaxy (MBE) on (001) InP substrates. InGaAs QW wafers consisted of an $In_{0.53}Ga_{0.47}As$ buffer layer, an $In_{0.52}Al_{0.48}As$ bottom barrier layer, an $In_{0.53}Ga_{0.47}As$ QW layer and an $In_{0.52}Al_{0.48}As$ top barrier layer. The thickness of the each layer was 600, 600, 5 and 50nm from the bottom to the top, respectively. Then, arrays of the unpassivated InGaAs wires were formed by standard EB-lithography followed by wet chemical etching in a phosphoric acid solution. Four kinds of wire arrays having different wire widths ,W , of 180, 310, 650 and 1150nm, were formed on a same QW wafer. An example of SEM micrographs of a wire array consisting of wires with a

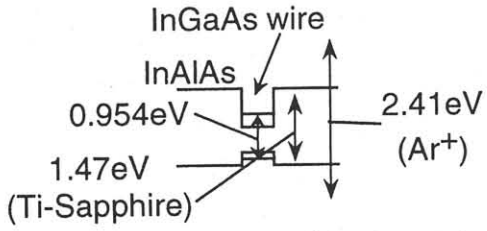


Fig.3 PL excitation sources used for characterization.

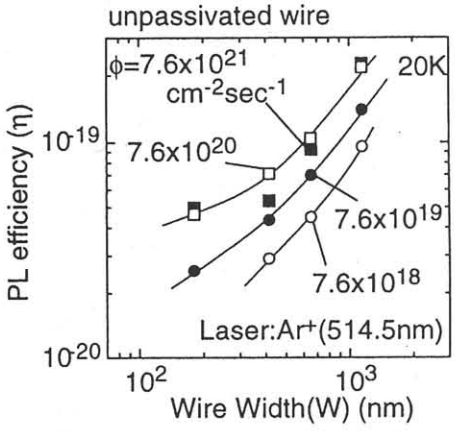


Fig.4 Observed relation between W and η for unpassivated wires

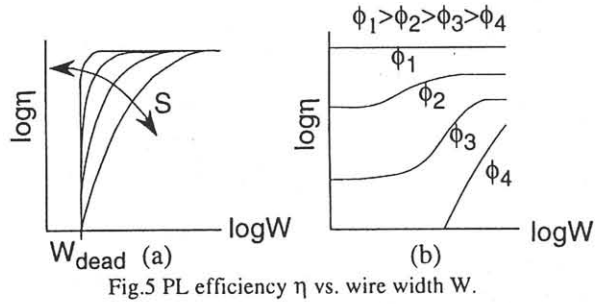


Fig.5 PL efficiency η vs. wire width W.

width, W, of 650nm, is shown in Fig.2. As shown in Figs.2(a),(b), each array had an area of 0.5 x 0.5 mm and consisted of 64 blocks with an area of 30 x 30 μm containing InGaAs wires with a spacings of 1μm. Fig.2(c) shows a SEM image of a single wire taken at a higher magnification. As shown in Fig.2(c), the side walls of the wire were (111)A facets. Uniformity of the wire sizes was quite good according to SEM observation. The edge passivation of the wires were done by applying the Si ICL-based passivation technique[1)-3)] to the surface of the air-exposed wire sample. Just before MBE growth of the Si ICL in the MBE chamber, the wire edges were etched by an HF solution in N_2 atmosphere to remove surface oxides.[7)] Then, an ultrathin Si ICL with a thickness of about 10Å was grown at the substrate temperature of 250℃ followed by photo-CVD deposition of a main passivation layer of SiO_2 with a thickness of 500Å under excitation by an ArF excimer laser(193nm).

The effect of the Si ICL-based passivation on wires was evaluated by change of their photoluminescence (PL) properties. Before and after passivation, PL was measured using an Ar+ laser (2.41eV) and a Ti-sapphire laser

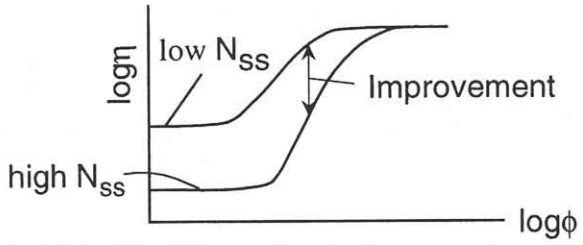


Fig.6 Principle of the novel excitation power dependent PL characterization.

(1.47eV). As shown in Fig.3, the former excites carriers in both wire and barrier region, whereas the latter excites on the wire region.

3. RESULTS AND DISCUSSION

Figure 4 shows the observed relationship between W and PL efficiency, η, for unpassivated wires taken at various excitation levels, ϕ, using the Ar+ laser as the excitation source. Here, η is the average PL quantum efficiency defined as the PL emission intensity per unit active area of the wire divided by the incident photon flux density ϕ from the excitation laser source. It is obvious from Fig.4 that the PL quantum efficiency depends on the incident photon flux density. Thus, these data cannot be fitted to the conventionally used theoretical curves, schematically shown in Fig.5(a),[8)] where a constant surface recombination velocity, S, and presence of a optically inactive "dead layer", with a constant width, W_{dead} ,are assumed.

On the other hand, the values of both S and W_{dead} depend on the flux density according to our recent study on the surface recombination process.[9),10)] Based on this picture of S=S(ϕ), more complicated ϕ-dependent behavior of the PL efficiency vs. wire width W, as schematically shown in Fig.5(b), is expected. Obviously, the data given in Fig.4 show such behavior and support such a picture. According to our previous analysis, the PL efficiency vs. the incident photon flux density behaves as schematically shown in Fig.6 for two wires with a high and a reduced density, N_{ss}, of surface recombination centers or surface states. At low values of ϕ , the PL efficiency takes a low constant value due to the fact that the effective surface recombination velocity becomes maximum. As ϕ is increased, the efficiency increases due to the saturation of surface states and band flattening. At large values of ϕ , the PL efficiency approaches an intrinsic value determined by the bulk radiative recombination processes. Thus, S is no longer a good measure of surface recombination, since it is strongly ϕ-dependent as easily inferred from Fig.6. On the other hand, a most straightforward way to see the effectiveness of the passivation is to measure η as a function of ϕ and determine the passivation-induced increase of quantum efficiency as shown in Fig.6. If necessary, one can estimate the N_{ss} distribution using the procedure described in reference.[9),10)]

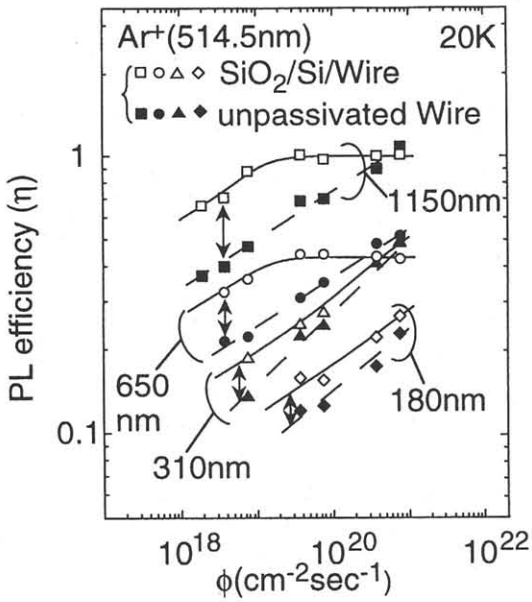


Fig.7 Relationship between η and φ mesured under Ar^+ laser excitation.

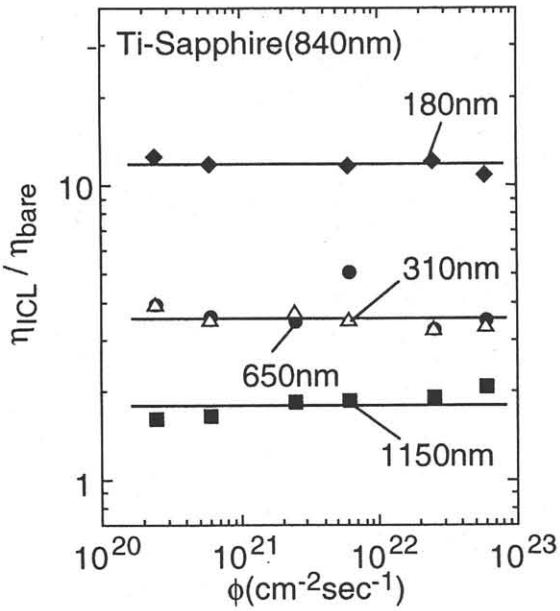
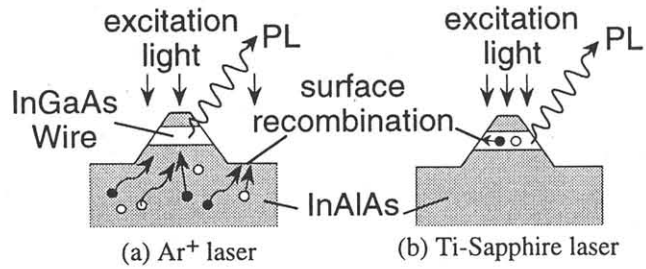


Fig.8 Relationship between η and φ mesured under Ti-Sapphire laser excitation.

The observed φ-dependences of η are summarized in Fig.7 for the unpassivated and passivated wires, under excitation by an Ar+ laser. The result obtained under excitation by a Ti-Sapphire laser is shown in Fig.8. As seen in Fig. 7 and 8, PL efficiencies were improved for all wires in both cases of excitation. However, degree of improvement as well as the detailed φ dependencies are considerably different between Fig.7 and Fig.8. In the case of the Ar+-laser excitation, the improvement is by a factor of 1.2-2 at low excitation levels after application of the Si ICL-based passivation. In the case of Ti-Sapphire laser excitation, on the other hand, improvement of PL efficiency by larger factors was observed. Particularly, more than 10 times enhancement of PL efficiency was achieved for the narrowest wire having W=180nm.

According to the previous discussion, the improved



(a) Ar^+ laser (b) Ti-Sapphire laser

Fig.9 Difference in surface recombination process due to excitation source wavelength.

PL efficiency in both cases can be attributed to the reduction of surface state density, N_{ss} after application of the Si ICL-based passivation. The difference in the η−φ behavior between Fig7 and Fig.8 can be explained by the following two reasons referring to the schematic representation of the surface recombination processes given in Fig.9(a) and 9(b). Firstly, the effective carrier injection level is much lower in the Ti-Sapphire case than that in the Ar+ case, because the light is absorbed and carriers are generated only in small and thin InGaAs wire regions in the former case as shown in Fig.9(b). Secondly, surface recombination far from the edge affects the result in the Ar+ laser case, as shown in Fig.9(a), whereas surface recombination takes place only at the wire edges in the Ti-Sapphire case as shown in Fig.9(b).

Thus, the Ti-sapphire result is more directly related to the surface recombination at the edges of InGaAs wires. Therefore, larger improvement in η as seen in Fig.8 indicates that large reduction of surface recombination takes place at the wire edges by applying the Si ICL-based passivation process. The observated fact that the factor of improvement in η increases with the reduction of W as seen in Fig.8 is consistent with such an interpretation since the relative importance of surface recombination on the PL efficiency should become larger in the narrower wires.

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