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Reduction of Surface State Density in InP by Laser Irradiation

Hideo Nakanishi and Kazumi Wada

NTT LSI Laboratories, 3-1 Morinosato Wakamiya,
Atsugi-shi, Kanagawa 243-01, Japan

A new phenomenon has been discovered in which Ar laser irradiation increases carrier density in InP. This indicates a reduction in surface state density, and corresponds to a 25% improvement toward the band flattening condition which is slightly over that induced by sulfur treatment. An AES study has demonstrated that this surface state reduction is due to the enhanced oxidation of InP by laser-induced photochemical reaction. Our finding of surface state reduction by laser irradiation has a good chance of producing a new dry passivation method.

1. INTRODUCTION

The high mobility and saturated drift velocity of electrons observed in InP make InP a very attractive material for high-speed circuit applications. However, its implementation is somewhat hampered by difficulties in reproducibly controlling its surface electrical properties. These difficulties are responsible for high densities in surface states and caused by semicondutor surface degraded during device processing. Surface state reduction is, therefore, essential to achieving InP-based high-speed circuits.

Native oxides are generally assumed to be poor candidates for passivating III-V semiconductors including InP. Therefore, most of the previous work to reduce surface states in InP has concentrated on the formation of good insulator materials. This includes chemical vapor deposition of dielectric layers,[1-2)] anodic oxidation,[3)] and sulfurization with $(NH_4)_2S_x$.[4)] However, these effots have, to date, been somewhat less than entirely successful. This is due to unavoidable problems encountered in each method. For example, P_2O_5-rich oxide grown by chemical vapor deposition reduces surface states but absorbs moisture from the air rendering its electrical properties unstable. Anodic oxidation and sulfurization also suffer from contamination caused by wet processes.

In this paper, we propose a novel method for reducing surface states in InP. It is based on our finding that laser irradiation enhances the surface oxidation of InP resulting in surface state reduction.

2. EXPERIMENTAL

Surface state reduction is generally observed as an increase in carrier density due to an associated narrowing of depletion layer width. Therefore, we used micro-Hall devices fabricated by Si implantation ($n=6x10^{12}/cm^2$) to demonstrate the laser irradiation effect. An Ar laser (514.5nm, 0.5-$5kW/cm^2$) irradiated the entire device area ($50\mu m$ x $50\mu m$) in an air and N_2 ambient for 0.5 to 60 min. Carrier density with and without laser irradiation was compared.

Sulfur treatment using an $(NH_4)_2S_x$ solution was also carried out and its effect on carrier density was compared with that of the laser irradiation.

Moreover, Auger electron spectroscopy (AES) measurements were carried out on InP wafers to study the chemistry in the near surface region after the laser irradiation.

3. RESULTS AND DISCUSSIONS

Figure 1 shows the typical behavior of carrier density after the laser irradiation in air. The horizontal axis indicates the elapsed time in darkness after which the device was subjected to the carrier density measurements. It can be seen that carrier density decreases with time, gradually approaching a constant value. This decrease in carrier density is due to a much slower relaxation of photoexcited carriers caused by weak illumination from the microscope used in the measuring setup as well as from the laser irradiation. This relaxation of the photoexcited carriers can be approximated by a linear combination of two exponential decay terms with time constants of 0.5 and 5 hours. It completely diminishes after a time lapse of more than about 20 hours. Therefore, in the present experiments, we eliminated the effect of photoexcited carriers by placing the devices in darkness for more than 20 hours prior to measuring.

Figure 2 shows the thus obtained carrier density increase due to laser irradiation. The horizontal axis indicates laser irradiation time. A carrier density increase due to laser irradiation in air is clearly observed, whereas no increase occurs in N_2. The in-air increase rises as high as $4\times10^{11}/cm^2$. This ambient dependence suggests that the increase results from a reduction in surface state density, but not from the annealing of carrier killer centers in the bulk. This is discussed below.

(i) Mobility does not show any increase, confirming that the carrier density increase is not due to the annealing of carrier killer centers. Raman spectroscopy also denies the annealing effect since the temperature rise during laser irradiation is only a few tens of degrees Celsius, as estimated from the ratio between the Stokes and anti-Stokes lines.

(ii) Sulfur treatment using an $(NH_4)_2S_x$ solution reduces the surface state and increases carrier density as much as $3\times10^{11}/cm^2$. This increase is comparable to that obtained in in-air.

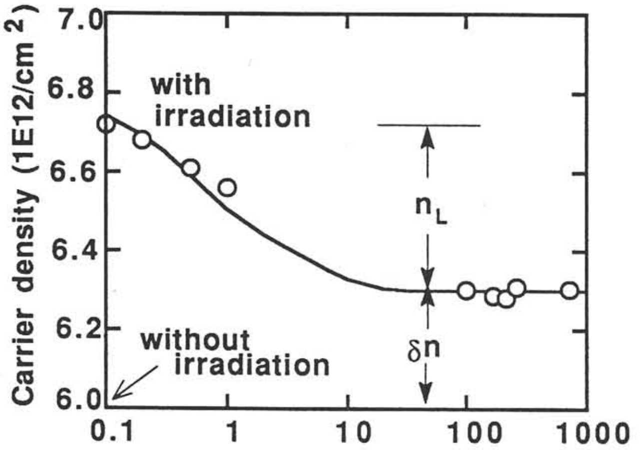

Fig. 1. Typical behavior of carrier density observed in Hall devices with in-air laser irradiation. The horizontal axis indicates the elapsed time after the devices are placed in darkness. n_L originates in photoexcited carriers and δn is the real increase in carrier density eliminating the influence of the photoexcited carriers.

These observations lead us to conclude that laser irradiation reduces surface state density in InP.

When the surface state density is reduced, the Fermi level approaches the bulk level (flatband condition) so that the depletion layer width, W, due to band bending narrows, resulting in an increase in carrier density, n. To evaluate the relaxation of band bending due to surface state reduction, we estimated the decrease in built-in potential, V_{bi}, from the present increase in carrier density, using the following relations,

$$n = N(D-W), \quad (1)$$

$$W = \{2\varepsilon(V_{bi}-2kT/qN\}^{1/2}, \quad (2)$$

where N is the bulk density of doped impurities, D is the depth of doped layer, ε is the permittivity, k is the Boltzmann constant, T is the temperature and q is the elemental charge. In the present case, N and D are roughly given as $1\times10^{18}/cm^3$ and 800 A, respectively. By assuming that V_{bi} without laser irradiation is 0.4V,[5] we can obtain the relationship between δn and V_{bi}, as shown in Fig. 3. It is found that the laser irradiation at a power of 5 kW/cm^2 for 60 min. reduces the built-in potential from 0.4 to 0.3 V. This is a 25% improvement toward the flatband condition and slightly more than that induced by sulfur treatment.

Reducing surface state density should be induced by InP surface oxidation, since a carrier density increase occurs in ambient oxygen. This is consistent with previous reports that anodic oxide reduces InP interface states.[3] In this experiment, oxidation may be enhanced by laser-induced photo-

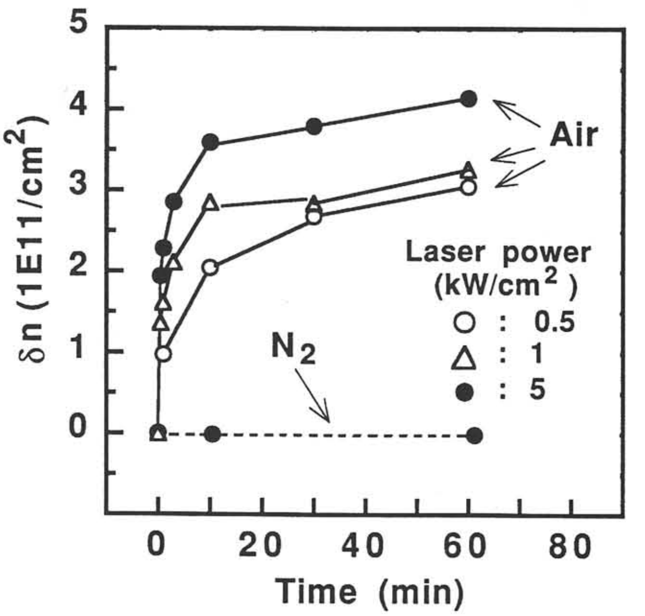

Fig. 2. Carrier density increase due to laser irradiation. The horizontal axis indicates laser irradiation time.

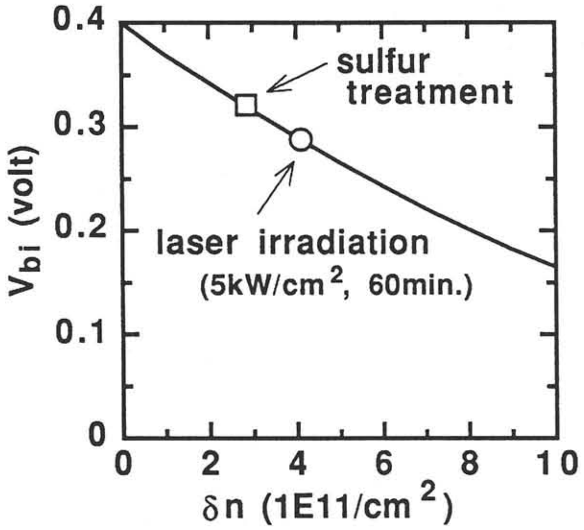

Fig. 3. The relationship between the built-in potential and the increase in carrier density.

chemical reaction. That is, InP activated by laser irradiation may react with oxygen diffusing through a thin native oxide, resulting in enhanced InP oxidation at the interface. To confirm the present idea of laser-induced oxidation, InP wafers were subjected to AES study after laser irradiation at 5 kW/cm^2 for 60 min. Figure 4 shows AES spectra in areas with and without laser irradiation. It can be seen that oxygen-related peak intensity in the area with laser irradiation is much higher than that in the area without irradiation. This is clear evidence that laser irradiation enhances InP oxidation. It is also seen in Fig. 4 that phosphorus-related peak intensity is reduced by laser irradiation. This suggests that the laser irradiation-induced oxide is more In-rich than the native oxide, although further studies including depth distribution analysis are necessary to provide information for discussing the chemical compositions of oxides.

4. SUMMARY

We have found that Ar laser irradiation increases the carrier density in InP, causing a reduction in surface state density. This effect corresponds to a 25% improvement toward the band flattening condition and is slightly more than that induced by sulfur treatment. An AES study has demonstrated that this surface state reduction is due to the enhanced oxidation of InP by laser-induced photochemical reaction. Our finding of surface state reduction by laser irradiation may be instrumental in producing a new dry passivation method.

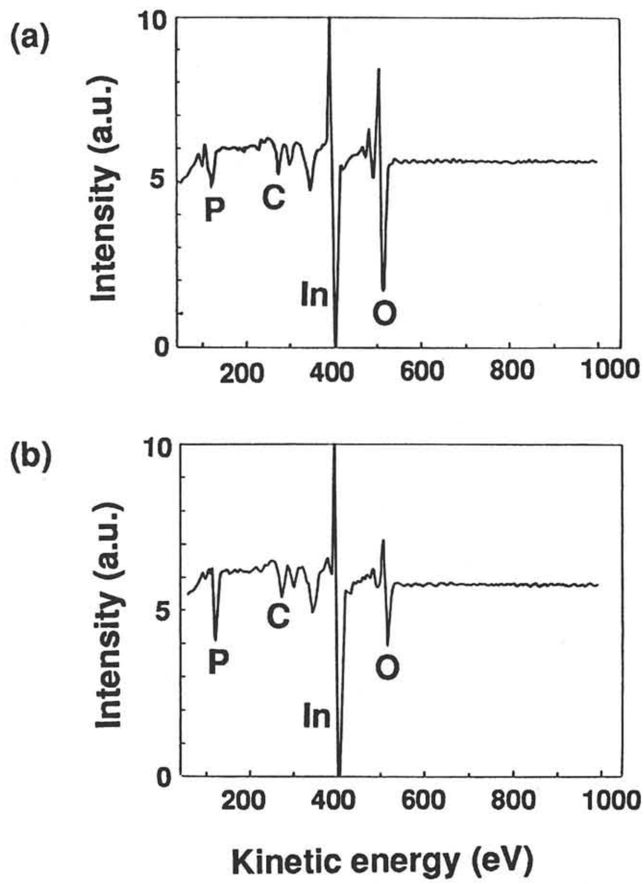

Fig. 4. AES spectra of InP. (a) With laser irradiation (5 kW/cm^2, 60 min.). (b) Without laser irradiation.

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