Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 640-642 

# High Responsivity in Optically Controlled Field-Effect Transistor Using Direct Wafer Bonding Technique

Takayuki SAKAI and Kazuhiko SHIMOMURA

*Department of Electrical and Electronics Engineering,*
*Sophia University*
*7-1 Kioi-cho, Chiyoda-ku, Tokyo 102, Japan*
*Tel +81-3-3238-3422 Fax +81-3-3238-3422*

An optically controlled field effect transistor (FET) in which the GaAs FET region and the GaInAs/InP light absorption region were directly bonded was demonstrated. This device has an advantage of high conversion efficiency of optical signal to electrical signal. In this work, we report the fabrication process for this device based on the direct wafer bonding technique, and show the bonding temperature dependence of the electrical and optical characteristics of these devices. As a result, we achieved high responsivity R∼150(A/W).

## 1. INTRODUCTION

We have demonstrated an optically controlled FET[1-4] which is a high speed optical detecting device as one of the key device for OEICs and optical interconnection. This device consisted of GaAs FET region and GaInAs/InP optical absorption region, and absorption of light modulates the electric field at gate of FET. As the one of the advantage of this device, it has high conversion efficiency of optical signal to electrical signal. In this report, we show the high responsivity of the optically controlled FET fabricated by direct wafer bonding technique.[4,5] We measured the dependence of the annealing temperature of direct bonding from the input optical characteristics of the device. As a result, we have achieved high responsivity R~150(A/W).

## 2. DEVICE STRUCTURE AND OPERATION PRINCIPLE

The structure of this device is shown in Fig.1. This device consisted of two parts. The upper was the light absorption region and the lower was the FET region. The absorption region was composed of GaInAs/InP materials and the FET region was the conventional GaAs MESFET structure. This device had four electrode that were p-electrode(Gate) and n-electrode at the absorption region, Drain and Source at the FET region. When light was irradiated on the absorption region, electrons and holes were generated, which were separated by applying a reversed bias voltage. Since these carriers move to opposite electrodes, the original applied voltage was screened by the carrier distributions. As a result, the electric field in the channel layer of the FET region was modulated, as was the drain-to-source current. Because the band-gap energy of the FET region was larger than that of the light absorption region, absorption of the irradiated light in the FET region was insignificant. In this device, current modulation of the FET was not due to the change of photogenerated carriers in the channel but to the electric field modulation. Hence, the operating speed of this device was determined by the drift velocity of the photogenerated carriers in the absorption region, and was independent of the diffusion time of the photogenerated carriers in the FET generated when light was irradiated on the channel of the FET directly. Because of these structure, high speed and high conversion efficiency operation can be obtained.

| layer | carrier concentration ($cm^{-3}$) | thickness (nm) |
|---|---|---|
| p-GaInAs | $1\times10^{18}$ | 50 |
| n-InP | $1\times10^{17}$ | 50 |
| i-GaInAs | $1\times10^{15}$ | 300 |
| i-InP | $1\times10^{15}$ | 30 |
| n-GaAs | $1\times10^{17}$ | 100 |

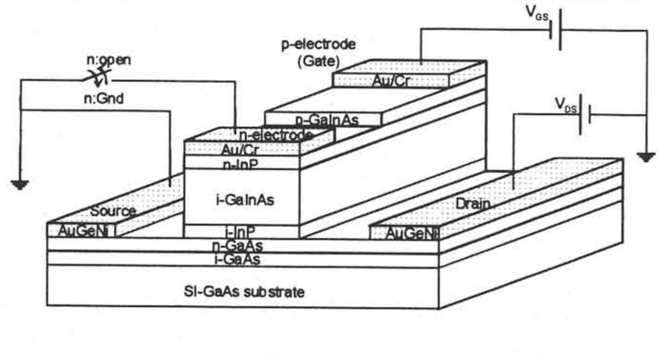



Fig.1. Schematic structure of optically controlled FET in which i-InP bonding layer of absorption region and n-GaAs layer of FET region were directly bonded.

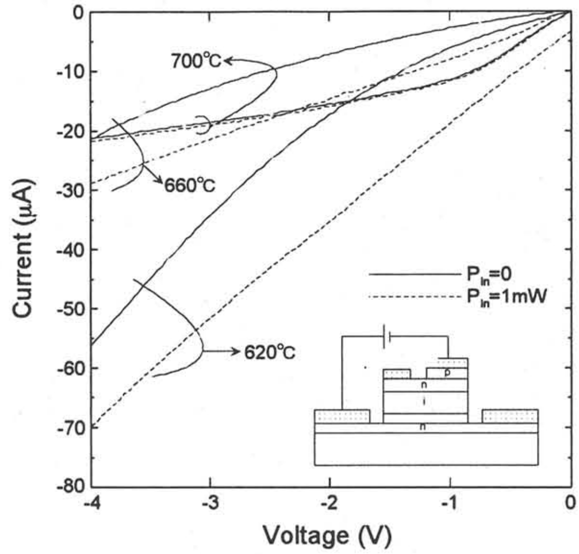
## 3. FABRICATION PROCESS

The wafers used in this work were (100) n-GaAs for the FET region and (100) p-InP/GaInAs for the light absorption region. The carrier concentrations were $1\times10^{17}cm^{-3}$ in the 0.35-μm-thick n-GaAs FET wafer and, $1\times10^{15}cm^{-3}$ in the 30-nm thick i-InP and 300-nm thick i-GaInAs layers, $1\times10^{17}cm^{-3}$ in the 50-nm thick n-InP layer, and $1\times10^{18}cm^{-3}$ in the 50-nm thick p-GaInAs layer in the absorption wafer. First, the wafers were cleaned using 50% HF solution and etched using $H_2SO_4$:$H_2O_2$:$H_2O$ solution (1:1:10 for InP, 1:1:40 for GaAs) to form hydroxyl molecules on the wafer surfaces.[5] After rinsing the wafers in deionized water, they were dried in air and bonded to each other at room temperature, under a weight of about $4kg/cm^2$ for 30 min. The weight was used to increase the self-adhesion between the hydroxyl molecules on the wafers. Then the wafers were placed in an annealing furnace and heated in $H_2$ atmosphere at 700℃, 660℃, or 620℃ for 30 min. A weight of $30g/cm^2$ was placed on the wafers during annealing. After annealing, the absorption region of the bonded wafer was polished down to a thickness of 20-30μm. Following the remaining p-InP substrate was removed using 4HCl:$H_3PO_4$ solution. To form a mesa structure in the light absorption region, the p-GaInAs, n-InP, i-GaInAs and i-InP layers were selectively etched to the top of the GaAs FET channel using 4HCl:$H_3PO_4$ solution for InP, and $H_2SO_4$:$H_2O_2$:$10H_2O$ solution for GaInAs. The mesa structure in the absorption region was 150μm wide and 440μm long. Then, the FET region was isolated using $H_2SO_4$:$H_2O_2$:$2H_2O$ solution, so that it became the same size as the absorption region and was patterned crossed with the absorption region. Finally, four electrodes were formed as ohmic contacts using AuGeNi for n-GaAs layers and Au/Cr for the p-GaInAs and the n-InP layer.

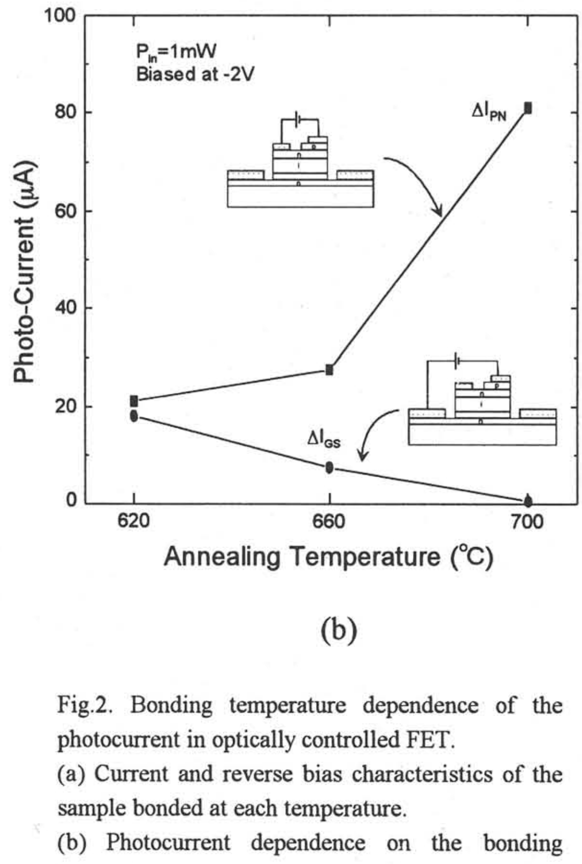
## 4. EXPERIMENTAL RESULTS

In the experiment, laser light with a wavelength of 1.55μm was coupled to a single-mode optical fiber, and the light output at the from end of the fiber was irradiated on the device directly. It was irradiated on the absorption region at an angle to the normal from above. The light input power $P_{in}$ was equal to the output power from the optical fiber. The electrical characteristics of the device were measured using a modular DC source/monitor (HP4142B).

Figure 2(a) shows the current and reverse bias characteristics of the sample bonded at each temperature. In these measurement, the reverse bias voltage was applied to the device in which it was applied to p-GaInAs layer of the absorption region and the n-GaAs layer of the FET region across the bonding interface. From this figure, the p-GaInAs/n-GaAs current $I_{GS}$ increased when bonding temperature decreased and it seems that photocurrent $\Delta I_{GS}$




(a)




(b)

Fig.2. Bonding temperature dependence of the photocurrent in optically controlled FET.
(a) Current and reverse bias characteristics of the sample bonded at each temperature.
(b) Photocurrent dependence on the bonding temperature.

increased when bonding temperature decreased. Figure 2(b) shows the photocurrent dependence on the bonding temperature when the voltage was applied to the p-GaInAs/n-InP ($\Delta I_{PN}$) and the p-GaInAs/n-GaAs layers. From this figure, the decrease of $\Delta I_{GS}$ by increasing the annealing temperature was caused by the increase of the resistance of the bonding interface. On the other hand, the increase of $\Delta I_{PN}$ was caused by the increase of leak current by the thermal damage of p-n junction in absorption region. The thermal damage to the absorption region that occurred

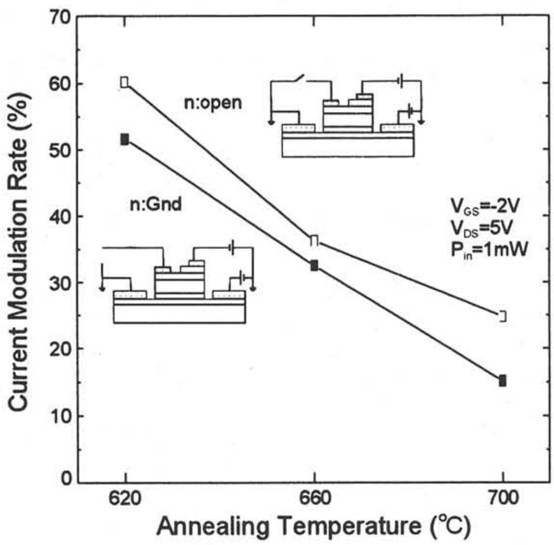



Fig.3. Relationship between current modulation rate of optically controlled FET and bonding temperature when input light power was 1mW.

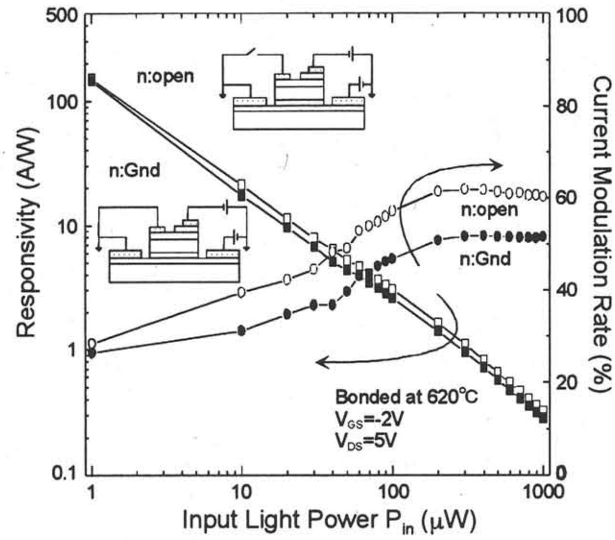



Fig.4. Input light power dependence of the responsivity and the current modulation rate for the sample directly bonded at 620℃.

during bonding was significant when the bonding temperature was higher than 660℃.

Figure 3 shows the relationship between the current modulation rate of the optically controlled FET and the bonding temperature where input power was 1mW. Here the current modulation rate is defined as the ratio of the difference between the drain-to-source currents with and without input light to the absolute drain-to-source current without input light, given by $\Delta I_{DS}/I_{DS}=((I_{DS}(P_{in}=0)-I_{DS}(P_{in}))/I_{DS}(P_{in}=0)$. From this figure, the optical to electrical conversion was increased by falling of the annealing temperature, because the modulation of electric field at the absorption region was more effective by the reduction of resistance of bonding interface and thermal damage of p-n junction. The current modulation rate obtained at a bonding temperature of 620℃ was three times that obtained at 700℃. Results for two current modulation rates are shown; that when the n-InP layers in the absorption region was electrically opened and that when it was grounded. When the n-InP layer was opened, only the photogenerated holes were swept out of the reverse biased layer, and the electrons remained in the absorption region. Both electrons and holes were swept out when the n-InP layer was grounded. When the n-InP layer was opened, the operating speed of the device was determined by the lifetime of the electrons, the electric field screening of the reverse bias was efficient and the current modulation rate was 5%～7% higher than when the n-InP layer was grounded.

Figure 4 shows the input light power dependence of the responsivity $R=\Delta I_{DS}/P_{in}$ and the current modulation rate for the sample directly bonded at 620℃. From this figure, the responsivity $R$=151.8(A/W) was obtained and modulation rate was ranged from 30% to 60%. These characteristics show the advantages of the high conversion efficiency of this device.

## 5. CONCLUSION

We demonstrated an optically controlled FET using direct wafer bonding technique, and measured the annealing temperature dependence of the characteristics of this device. We obtained the maximum responsivity R=151.8(A/W). It was confirmed that this device has high optical to electrical conversion efficiency.


## ACKNOWLEDGMENT

The authors would like to thank Professors.K.Kishino and K.Shono of Sophia University for fruitful discussions. They would also like to acknowledge Mr.S.Suzaki and Mr.T.Aizawa, Fujikura Ltd. for supplying the wafers.


## REFERENCES


1) K. Shimomura: Jpn. J. Appl. Phys. **31** (1992) 1757.
2) Y.Shimizu and K.Shimomura: Jpn. J. Appl. Phys. **33** (1994) L109.
3) Y.Shimizu and K.Shimomura: IEEE Photon. Technol. Lett. **6** (1994) 1338.
4) T.Sakai and K.Shimomura: Tech. Dig. Tenth International Conference on Integrated Optics and Optical Fiber Communication, Hong Kong, June 1995, FA-3-6.
5) H.Wada, Y.Ogawa and T.Kamijoh: Appl. Phys. Lett. **62** (1993) 738.