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Phototransistors Using Point Contact Structures

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We report on the photoresponse of the point contact structures under laser illumination condition. The point contacts showed phototransistor action with large responsivity more than 10^5 A/W and large on-off rate probably due to efficient hole localization in the point contacts. As applications, we demonstrate the optical subtraction circuit using two point contact phototransistors and the optical amplifier using a point contact phototransistor and a light emitting diode.

1. INTRODUCTION

Semiconductor nanostructures have received much attention for quantum device applications. Transport or optical properties have been individually investigated so far.[1, 2] At the next step, it is important to study these properties simultaneously in order to obtain more detailed information and new ideas for applications. In the previous papers we demonstrated photon-assisted tunneling through a point contact structure under microwave illumination condition.[3, 4]

On the other hand, optical processing and computing have recently become significant for achieving neural network systems. Various approaches have been proposed and actually integrated circuits have been fabricated.[5-7] However, optical devices for this field are not sufficiently prepared. These devices have complicated structures, so that fabrication is not so easy. More simple structures are desired.

In this work we investigated transport properties of the point contact samples, which were fabricated by the regrowth technique, under visible light illumination condition, and found that the sample showed phototransistor action. The point contact phototransistors (PCPTs) have large responsivity and on-off rate although they have simple structure. As applications, we demonstrated the optical subtraction circuit and the optical amplifier using the PCPTs.

2. EXPERIMENTAL

2.1. Sample Fabrication

Samples including point contact structures were prepared by molecular beam epitaxy (MBE) of a modulation-doped n-type $In_{0.17}Ga_{0.83}As$/GaAs quantum well with a thickness of 10 nm, followed by the formation of constrictions with widths of 100 - 500 nm and a length of 200 nm by wet etching, and regrowth of GaAs by MBE for embedding the etched grooves.[8] Carrier density and mobility of the unetched quantum well under dark condition at room temperature were 6.0×10^{15} m^{-2} and 0.42 m^2/Vs, respectively. In the same wafer we also made Auston-switch-like samples in which a constriction was perfectly etched away.

Since the InGaAs point contacts are embedded by GaAs and hydrogen cleaning was performed before the regrowth, there should be virtually neither non-radiative nor pinning centers at the regrowth interfaces.[9]

2.2. Micro-Photoconductivity Measurement

Micro-photoconductivity (μ-PC) measurements were carried out with a cw HeNe laser with a TEM_{00} mode which was focused onto the area around the point contact by an objective lens of an optical microscope. The numerical aperture of the lens was 0.42 and the working distance 17 mm. The wavelength of the laser was 632.8 nm and thus the beam diameter was 0.75 μm which is almost equal to the spatial resolution of the measurement system. The laser beam shape and size were checked by monitoring the reflection image by a conventional charge-coupled device (CCD) camera through the same objective lens. For monitoring the position of the laser beam against the point contact, a white light illumination by a tungsten lamp was used.[10] The change of μ-PC of the point contact was measured as a function of laser beam position, laser power, or bias voltage which was applied between the source and the drain. Here, note that most of the bias voltage is applied in the point contact. For measuring μ-PC as a function of wavelength, output light from a double-monochrometer was used, where a tungsten lamp was set at the input of the double-monochrometer. Spectral profile of the light was measured by a power meter, and the data were used for obtaining precise μ-PC profile of the samples.

3. RESULTS AND DISCUSSION

3.1. Phototransistor Action

Figure 1 shows the drain current profiles of the point contacts with various width of 500, 300, 200, and 100 nm as a function of HeNe laser power at room temperature, where the bias voltage was changed from 0.2 to 1.0 V with a step of 0.2 V and the laser beam less than 300 pW was irradiated just on the point contact. As shown in these figures, current for the wide point contact is a little influenced by the laser illumination. However, with decreasing the width of the point contact, current at 0 pW largely decreases and approaches to zero while totally current decreases because of decrease of the sample conductance.

Figure 2(a) and 2(b) show the conductance at laser powers of 0 and 300 pW and a bias voltage of 1 V, and the responsivity at 5 pW and 1 V as a function of width of the

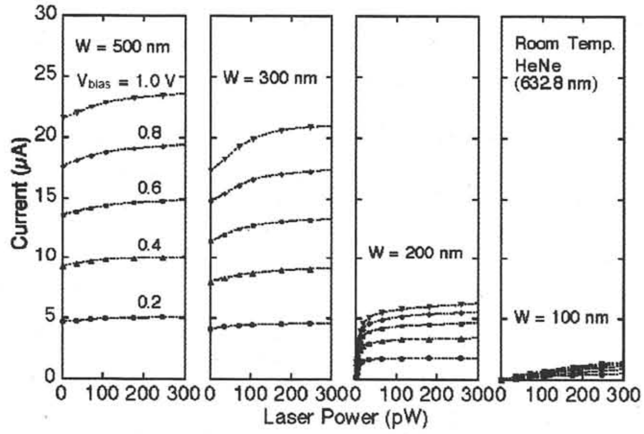

Fig. 1 Drain current profiles of the point contacts with various widths as a function of HeNe laser power at room temperature, where the bias voltage applied between the source and the drain was changed from 0.2 to 1.0 V with a step of 0.2 V as indicated at the right side of each curve for the 500-nm sample.

point contact, respectively, which were derived from Fig. 1. From Fig. 2(a), one can see that narrow point contacts are also conductive because they are embedded in the GaAs lateral barriers, while only etched point contacts of InGaAs with low In content are not conductive as the width becomes less than about 400 nm due to depletion from the etched surfaces. Moreover, recombination of electron-hole pairs is non-radiative and very fast in the etched samples.

Large responsivity 2×10^5 A/W is estimated for the 200-nm point contact sample as shown in Fig. 2(b). This large responsivity or optical gain is considered to be due to efficient hole localization in the point contact. We measured photoresponse as for the Auston-switch-like sample, and obtained responsivity of about 2 A/W which almost corresponds to a quantum efficiency of 100 %. Therefore, it is considered that quantum efficiency of the PCPTs is also near 100 %.

Figure 3(a) shows AC current through the 200-nm PCPT measured by a lock-in amplifier with a modulation frequency of about 200 Hz as a function of wavelength of the spectral-resolved incident light, where power of the light was strongly reduced less than 5 pW, the light diameter on the sample was set less than 1 μm, and the light was irradiated just on the point contact. As shown in

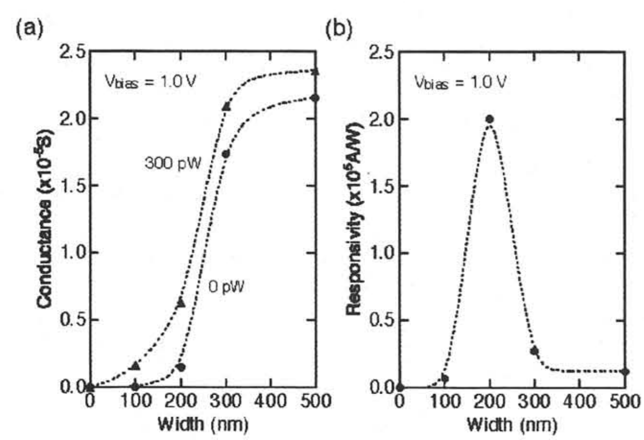

Fig. 2 Conductance at laser powers of 0 and 300 pW and a bias voltage of 1 V.(a) Responsivity at 5 pW and 1 V as a function of width of point contacts.(b)

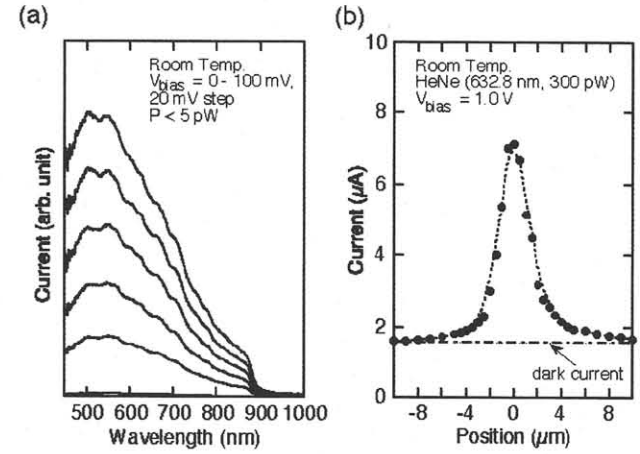

Fig. 3 Current through the point contact with a width of 200 nm measured by a lock-in amplifier as a function of wavelength of the spectral-resolved incident light, where power of the light was less than 5 pW, the light diameter on the sample was set less than 1 μm, and the light was irradiated just on the point contact.(a) Current through the point contact measured in changing the position illuminated by the laser beam. (b)

this figure, an absorption gap is seen at a wavelength of about 870 nm, which corresponds to the band-gap of GaAs. Therefore, it is considered that most of light is absorbed in the GaAs barrier, and generated holes drop into the InGaAs point contact which effectively reduces height of the conduction band of the point contact, and then majority electrons can go through the point contact. While under no illumination condition majority electrons can not pass the point contact because height of the conduction band of the point contact becomes higher in the influence of the lateral GaAs barriers.

This idea is supported by the result shown in Fig. 3(b). Here, current through the point contact was measured in changing the position illuminated by the laser beam. In this figure, current shows maximum when the laser beam was irradiated just on the point contact, but the current curve is broader than the beam size, and the curve dose not have perfect symmetry and shows small broadness in the right side. This shows that hole movement into the point contact occurs from the around area and that the small asymmetry is caused from the hole movement by the electric field of the bias voltage.

We also investigated on the GaAs/AlGaAs point contact structures fabricated by the hydrogen-assisted selective growth technique using MBE.[11] These samples were *in situ* fabricated, so that the growth interfaces should have the same grade as that of quantum well samples. Also as for these samples, similar results were obtained. Moreover, longer point contacts showed larger responsivity, which is different from the result concerning previous photoconductive detectors.[12] From these results, it is considered that the present phototransistor action relates not to minority-carrier traps[13] at the surface or the growth interfaces but to the hole localization in the point contacts.

3.2. Applications

We constructed the optical circuit for subtraction using two PCPTs as shown in Fig. 4(a), where a chopped laser beam with a frequency of 400 Hz and that with a little different frequency are irradiated onto the two point

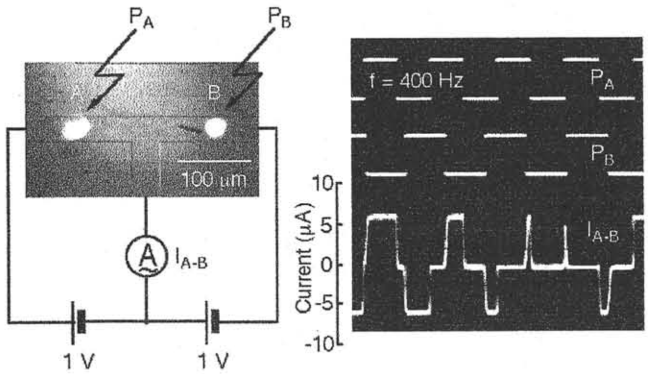

Fig. 4 Optical circuit for subtraction using two PCPTs,(a) where a chopped laser beam with a frequency of 400 Hz and that with a little different frequency are irradiated onto two point contacts, respectively. (b) shows the experimental result, where P_A and P_B correspond to the change of the laser power of the two laser beams and the lowest profile $I_{A\text{-}B}$ is AC current measured by the ammeter shown in (a).

contacts, respectively. Here, subtraction is the basic calculation for realizing neuron devices,[14] and is desired to be carried out by more simple structures.

Figure 4(b) shows the experimental result, where P_A and P_B correspond to the change of the laser power of the two laser beams and the lowest profile $I_{A\text{-}B}$ is the current measured by the ammeter shown in Fig. 4(a). As shown in this figure, one can see subtraction is actually performed by the present circuit.

By using a PCPT and a red LED, we constructed an optical amplifier as shown in the inset of Fig. 5. Here, the PCPT with a size of 1 x 1 mm^2 includes 20,000 point contacts with a width of about 150 nm in parallel for obtaining large drain current and large on-off rate, and the LED has an efficiency of 10 %. Main part of Fig. 5 shows output light power of the LED as a function of input light power irradiated on the PCPT. Here, we can obtain large gain more than 20.

The conduction area of the present structure is made by

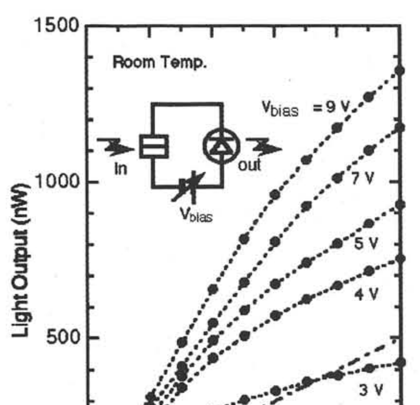

Fig. 5 Output profile of the optical amplifier using a point contact phototransistor and a light emitting diode as a function of input light power at room temperature. A inset shows the circuit, and a chain line indicates a gain of 10.

modulation-dope technique, so that there is an advantage that the electron mobility is large, therefore high speed devices are expected.

Moreover, the structure of the lateral point contact fabricated by regrowth technique is easily changed into vertical structures. Vertical structures have advantage for making lamination structures with other devices, therefore the present fabrication method is promising for laminating. The light output from the LED is incoherent and also independent to the input light phase because the input light is once changed into electron flow. Vertical structures and combination of laser diodes may improve such situations.

4. CONCLUSION

We investigated detailed photoresponse of the point contact structures and found that the structures showed phototransistor action with extremely large responsivity. We applied these PCPTs for constructing an optical subtraction circuit or an optical amplifier. The PCPTs or their applications are promising for general optical circuits or neural network systems such as smart pixels.[14]

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