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Optical-beam profiling by bias-controlled metal-semiconductor-metal structures

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1. Introduction

Recently we have shown experimentally that a planar metal-semiconductor-metal(MSM) structure having a wide separation between the two metal electrodes exhibits not only the function of a basic optical sensor but also optical sensitivity field-controllable by the bias applied [1]. In this study, we present the experimental results of one-dimensional (1D) optical-beam profiling properties of an MSM structure as its application. To our knowledge, no study has appeared on such an application of planar MSM structures.

2. Model of operation

The essential cross-section of the structure we treat in this study is illustrated schematically in figure 1. The separation between the electrodes located at both ends is wide enough to leave the undepleted neutral region under the bias we examined. When a bias voltage is applied between the electrodes, one Schottky-junction is reverse-biased and the other junction is forward-biased. Such a structure is expected to show lateral spreading of its space-charge-region (SCR) of the Schottky-junction reverse-biased towards the other electrode is expressed semi-empirically[1].

$$W(V_a) = \sqrt{\beta(V + V_a)} \qquad (1)$$

where $W(V_a)$ is the width of lateral spreading of the SCR along the surface of the active area at an applied bias V_a, $\beta = 2\varepsilon_s/qN_D$, ε_S is the permittivity of the semiconductor employed, q is the elementary charge, N_D is the impurity concentration and V_0 is the built-in voltage of the Schottky-barrier, respectively. The barrier on the other side is forward-biased and assumed here to be nearly flattened. The photoinduced current $I_P(V_a)$ is approximately formulated as [1,2]

$$I_p(V_a) = \eta[kW(V_a) + L] \qquad (2)$$

where L is the diffusion length of the mobile carriers and k means that the SCR is k-times more effective to generating

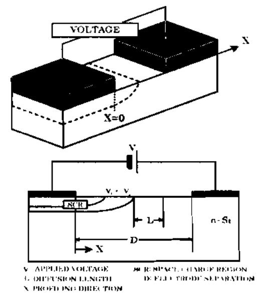

Fig 1. Schematic illustration of an MSM structure, leaving an undepleted region even under a bias.

the photocurrent than the residual undepleted region (presumably, larger than unity, and η is the proportionality factor including the effect of quantum efficiency and intensity level of irradiation. As a result, $I_P(V_a)$ is would be an increasing function of applying bias V_a with the dependence on $\sqrt{V_0 + V_a}$ This means that the device structure under consideration is to furnish the field-controllable iris.

3. Experimental

To make the electrodes of $3\times3\,\mathrm{mm}^2$, molybdenum film working also as barrier metal was deposited onto an n-type silicon wafer by an electron-beam evaporator and was subsequently processed by photolithography lift-off technique. The electrode separation is mainly 2000 μm. The resistivity of the wafer used was (40-50)Ωcm. This resistivity would provide corresponding donor concentration of some $3\times10^{16}\mathrm{cm}^{-3}$. The height of the Schottky-barrier on both sides was estimated to be (0.55-0.65)eV from the forward current–voltage characteristic[3]. Furthermore, from this value of the barrier-height, the built-in voltage V_0 is deduced to be approximately 0.23 eV

We carrier out of profiling of the light-beam from a He-Ne laser having a wavelength of 633nm. The optical beam was scanned by every 15 μm in the perpendicular orientation of the tilting plane of the beam. Spatial intensity distribution of the beam to be detected was assumed to be Gaussian distribution with the radius (2σ) of 480 μm defined at the point of $1/e^2$ its maximum just at the aperture of the light source quoted by the manufacturer. The dispersion angle of the beam from the source is approximately 0.23 $mrad$. To control the light intensity incident onto the sample, a neutral density (ND) filter was utilized.

4. Result and discussion

First, we observed the x-direction 1-D spatial distribution of detected photocurrent over the whole region between the electrodes. The typical plot for a 2000 μm separated electrode sample is shown in figure 2. The photocurrent was obtained by subtracting the dark current from the current as measured at the same bias. Each peak in the figure 2(a) and (b) corresponds to the profile when the polarity of bias is reversed. From the figure (a)and(b), the separation of the two peaks is estimated to be about 1920 μm, which is a little smaller than the electrode separation. It is apparent from these figures that only the SCR of the junction reverse-biased generating photocurrent.

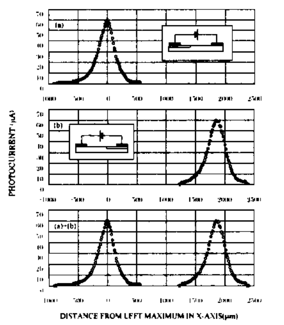

Fig. 2. Spatial distribution of the photocurrent under a constant optical illumination level versus the lateral position of every 15 μm step. Electrode separation is 2000 μm.

On the contrary, the current from the barrier forward-biased barrier is extremely small and can substantially be ignored. As described the photocurrent vs. position relationship for the sample appeared in figure 2 under a fix bias of 16V were observed under three different illumination intensity levels. The plot normalized at each maximum are shown in figure 3, where the solid line represents the Gaussian curve calculated using the parameters given by the manufacturer of the light source.

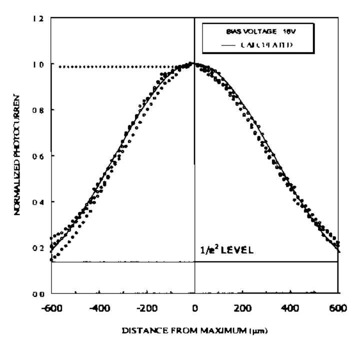

Fig.3. Normalized plot of the spatial current distribution from the data in figure 3. Solid line represents the calculated Gaussian distribution for reference, taking $2\sigma = 480\mu m$.

We also carried out profiling by changing the bias voltage. Figure 4 shows the experimental plots for V_a=2V, 4V and 16V biases. These results show that with increase in bias the observed output photocurrent also increases. In the present experiments, the silicon wafer of the resistivity of (40-50)Ωcm for preparing samples. From equation (1), this resistivity expects the change in the width of the SCR, $W(V_a)$, from 6 μm to 16 μm at most between 2V and 16V. As a result, it can be concluded that the planar MSM structure examined can be used as a simple intensity profiler of an optical-beam of this size. As described earlier, the profiling was carried out changing the relative position by every 15 μm step, which is still larger or approximately equal comparing to the width of the SCR. Therefore, it can be mentioned that the beam profiling would still be effective. We repeated the similar measurements on the structure having 20 μm electrode separation. This result might be attributed that the SCR is several times more efficient than the same area within the diffusion length in generating photocurrent. Therefore, one can mention that the structure examined in this study is usable as a pixel for 1D optical-beam profiling, having the field-controllable sensitivity.

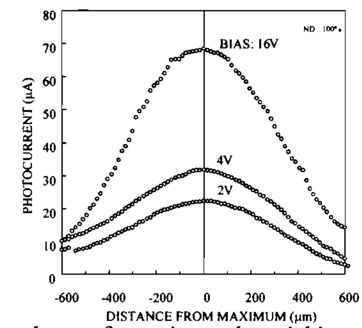

Fig.4. Bias dependence of experimental spatial intensity distribution for V_a = 2V,4V and 16V.

5. Conclusion

As a novel application, a planar MSM structure has been applied to profiling of the spatial intensity distribution of an optical beam in visible range. The Gaussian intensity distribution of the beam from a He-Ne laser was confirmed experimentally. The MSM structure proposed in this study also exhibits field-controllable sensitivity making use of lateral spreading of the SCR at the active surface.

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