Avalanche gain and Shot noise in silicon-based planar MSM structures

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Abstract

The properties of planar metal-semiconductor-metal (MSM) optical sensor structures on dc photocurrent gain have been investigated an experimentally. The structure has two co-planar Mo/n-Si Schottky-barrier junctions on silicon of resistivity 9-12 Ω-cm and the electrode separation is 2000 μm. The current-voltage (I-V) characteristics measurements under illumination in visible range showed a rapid increase in photocurrent at higher biases examined. The dependence of I-V characteristics and noise measurements, such photocurrent increase was ascribed to avalanche multiplication of carriers photogenerated in the Schottky junction as applied reverse-biased. From low -frequency (10-50kHz) signal measurements, it was found that multiplication factor larger than 100 at 10kHz and 30 at 50kHz was achieved.

Keyword: photocurrent, shot noise, MSM photodiode

1. Introduction

With an increasing demand of optical signal processing, planar metal-semiconductor-metal (MSM) optical sensor structures have attracted much attention as visible structures for application to optoelectronics systems [1]. Since a silicon material is the most extensively employed for semiconductor devices, an internal photocurrent gain provided by avalanche multiplication is of interest for higher optical responsively. The communication system have been examined simple Si-based MSM optical sensor structures, aiming at static (dc) photocurrent enhancement. In this research are presented the shot noise (white noise) in planar Mo/n-Si/Mo photodetector structures having long neutral region at low frequency regions.

2. Experimental

The samples were prepared as follows. We performed electron-beam evaporation of Mo 3000 Å thick at an initial vacuum of about 3×10^{-4} Pa onto an n-type silicon of resistivity of 10 Ω-cm. Mo thin film so formed works as Schottky-barrier metal to silicon and electrodes as well. The inset in Figure 1 shows the configuration of the electrodes, which was completed by photolithography lift-off technique. The size of both electrodes is the same (symmetrical) and of $3\times3\text{mm}^2$.

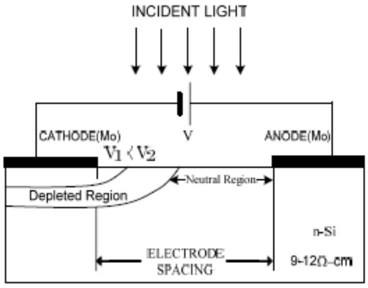


Fig.1 Schematic illustration of MSM structure having widely-separated electrodes under a bias.

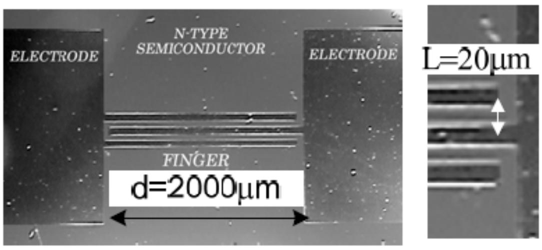
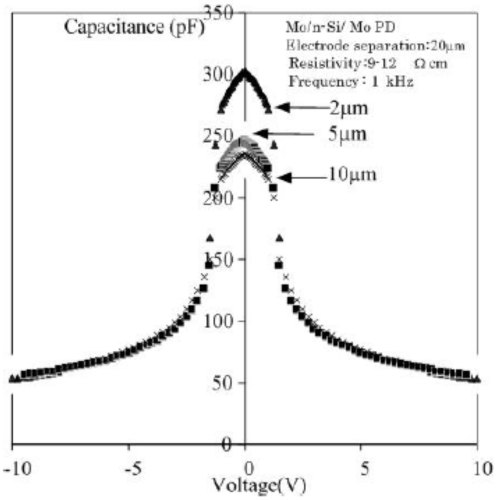


Fig.2 Photograph of an experimental Schottky-barrier MSM optical sensing chip by a CCD camera.

The sample is of 3 finger slit type in Figure 2. The finger width and spacing are 20 μm. Furthermore, the separation between the electrodes is 2000 μm, which is wide enough for the two depletion regions of both junctions not to contact each other even when bias is applied. Under a bias, the anode is forward-biased and the cathode is reversed-biased. From the forward current-voltage (I-V) characteristics and capacitance-voltage (C-V) characteristics under dark of independent Schottky-barriers shown in Figure 3, the barrier height and built-in voltage were estimated to lie around 0.70 eV and 0.23 eV, respectively [2].



Fig, 3 Capacitance-voltage (C-V) characteristics of a Mo/n-Si/Mo structure having 2,5 and 10μm electrode separation.

3. Measurement procedure

The current versus applied bias (I-V) characteristics were measured under optical illumination and in the dark conditions. The block diagram of the set up for measurements of I-V characteristics is shown in Figure 4. A neutral-density (ND) filter was used to control the device under test.

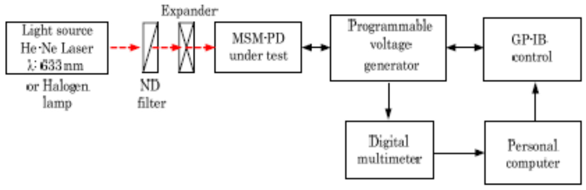


Fig.4 Block diagram of current-voltage I-V characteristic measurement system PC- controlled.

4. Result and discussion

Figure 5 shows the typical photocurrent versus relations at room temperature under different illumination levels from a halogen lamp. Here the photocurrent component was obtained by subtracting the current under dark from the device current at each corresponding bias voltage. Each plot seems to be divided into two regions: the gradually increasing and rapidly increasing regions with bias. Since the present sample has the electrodes widely separated to avoid electronic interference between two junctions, the lateral separated in the depleted region would be more efficient to generate the photocurrent than the residual undepleted neutral region. This would be the reason why the total photocurrent shows gradual increase with bias. The other region showing rapid increase in the photocurrent above about 12V seems to be under the onset of avalanche breakdown of the Schottky-junction reversed-biased, where the junction on the other side is, of course, forward-biased and it band structure is almost flattened. It has generally been accepted that, for a semiconductor junction, the breakdown characteristic at voltages smaller than $6E_g/q$ are attributed to the tunneling, where E_g is the band-gap of the semiconductor considered and q is the elementary charge [3]. This charge in build-up voltage suggests that the avalanche breakdown process is sustainable in this structure [5].

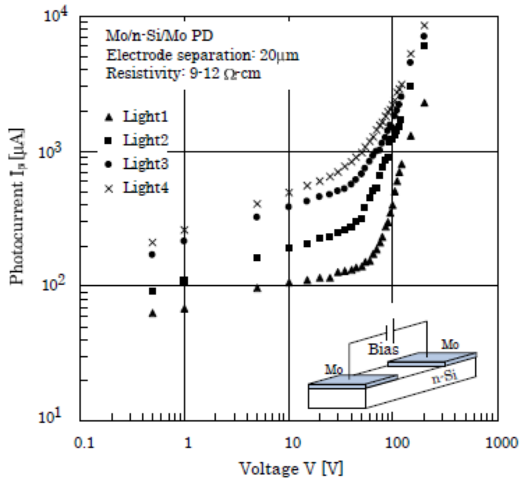


Fig. 5 Photocurrent-voltage characteristics of a Mo/n-Si/Mo structure having 20μm electrode separation.

As is well known, the avalanche process is inherently noisy process coming from stochastic ionization of carriers in high field. To more clarify the onset and sustaining of avalanching, we also carried out shot noise measurements at frequencies 10-50 kHz on Figure 6.

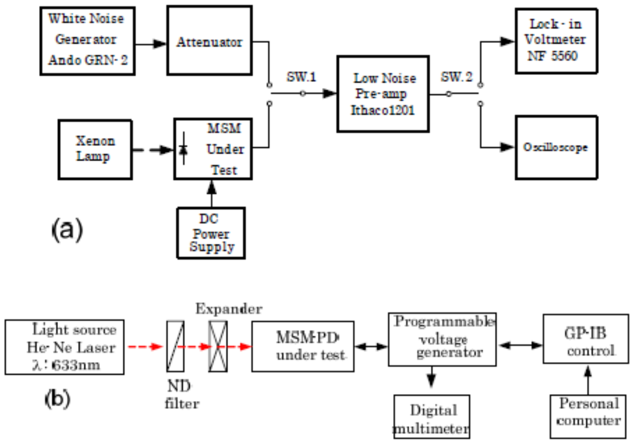


Fig. 6 (a) Block diagram of noise measurement system. For calibration of the system and noise observation in time domain, sw.1 and sw.2 are switched, respectively. (b) Schematic diagram of the setup for photo response measurements.

The noise measurements were performed using the system on Figure 6(a). The noise to be detected was introduced into a 2kΩ load resistor series-connected with the device under test; the voltage drop across the load was then introduced to a low-noise preamplifier and finally detected by a lock-in voltmeter.

To check the system characteristic, a white noise generator was used. To irradiate the device, a xenon lamp dc-operated was used as a light source, the intensity of which was controlled by an ND filter. Figure 7 shows the 10kHz current noise versus photocurrent relationship on log-log scale at two biases 10V and 80V, where dashed line indicates full shot noise, the corresponding noise factor is unity. At low frequencies where the noise is independent of the frequencies, the current noise spectral density associated with the average current I is usually formulated as already given in Eq.(1).

$$S(\omega) = 2qI\Gamma^2 (\mathrm{A}^2/\mathrm{Hz}) \qquad (1)$$

where Γ^2 is the noise ratio or the noise factor representing the ratio of the noise to full shot noise. One finds that the noise at 10V is proportional to the photocurrent, showing the noise is sub-shot noise and thus the noise factor of which is smaller than unity $[\Gamma^2 < 1]$. Incase of the bias of 80V, however, proportionality relation still holds up its level becomes much higher than the full shot noise observed originates from the avalanche multiplication of the photocurrent.

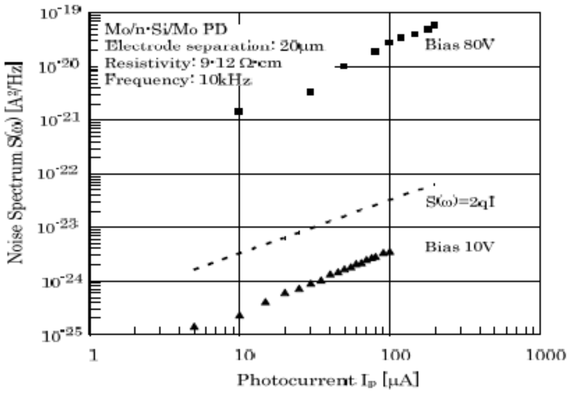


Fig. 7 Noise spectral density at 10 kHz versus photocurrent of Mo/n-Si/Mo structure, taking the bias voltage as a parameter.

In order to confirm that result, we carried out treat the low frequency optical signal response of the planar MSM structures proposed. The purpose of this section is to present the influence of operating condition on applied bias at the low frequency (50kHz) photoelectric response of planar Mo/n-Si/Mo structure with long neutral region. Optical response was measured using sinusoidal modulated He-Ne laser signal via an acousto-optic modulator (AOM). Figure 6(b) shows the block diagram for measurements of ac characteristics. An ND filter was used to control the light intensity and thus the photocurrent of the device. The signal to be detected was fed to a load of 2kΩ connected in series with the device under test.

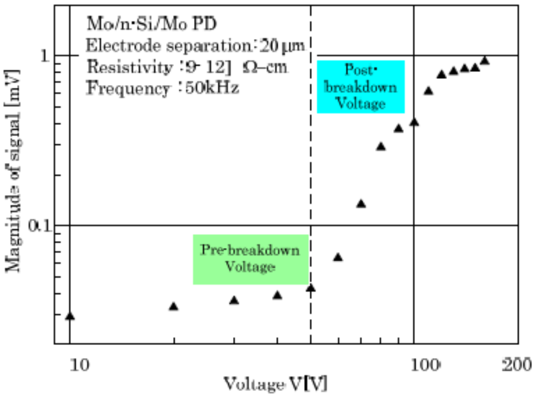
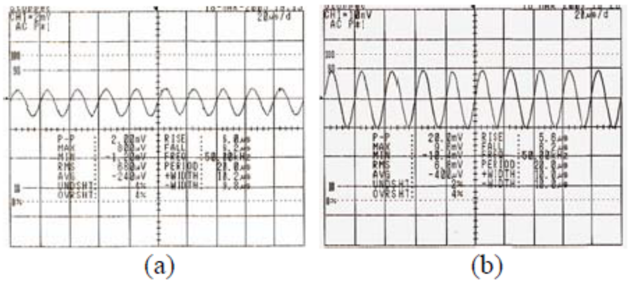


Fig. 8 Spectra of the demodulated signals at biases V=10V to 180V(b) at 50 kHz for the same device in frequency domain by an FFT spectrum analyzer.

Then, the voltage drop across the load was conducted to an oscilloscope to observe instantaneous demodulated signals or to a Fast Fourier Transform (FFT) spectrum analyzer to view the signals received in frequency domain at biases 10 V to 30V as shown in Figure 8. It was found that before breakdown (10-30V) the magnitude of output signal is dependence of applied bias. When the bias is towards near breakdown voltage (30-180V), the level of output signal much higher level is due to avalanche multiplication at high fields or hole injection from the anode. Because of the carrier multiplication due to impact ionization, the current entering the depletion layer is multiplied by factor, M, known as the multiplication factor, as it crosses the layer.



(a) (b)

Fig.9 Detected signal waveform at 50 kHz under pre-breakdown (a)-(b) and post-breakdown conditions in Mo/n-Si/Mo structure.

Optical signal sinusoidal intensity-modulated was detected by the structures under pre-breakdown and post-breakdown regions. Figure 9 (a) and (b) show the typical oscilloscope traces of the output signal versus bias voltage characteristics at frequency 50 kHz detected at two biases, 10Vand 80V, respectively. In this figure the amplitude of the demodulated waveform increases from 2.0 mV (peak-to-peak) at a bias V=10V to 20 mV at V=80V apparently showing the bias controlled iris effect is occurring. Apparently the amplitude observed under breakdown condition (bias: 80V) is approximately one decade (40dB) larger than that below the breakdown voltage (bias: 10V).

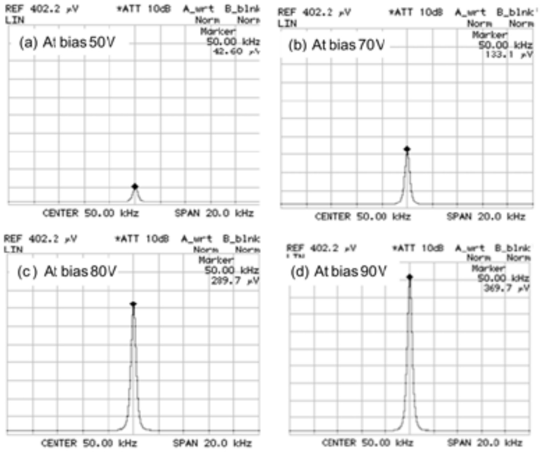
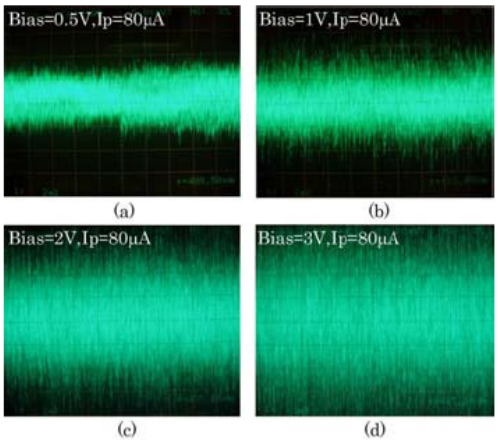


Fig.11 Detected signal waveform at 50 kHz under pre-breakdown (a-b) and post-breakdown (c-d) conditions in Mo/n-Si/Mo structure are the represented peak spectrum corresponding to biases, respectively.

Even at 50 kHz, 30dB gain was obtained. Figure 10(a-d) show the frequency spectra of the detected signals under pre-breakdown and post breakdown conditions, respectively. Although that the increase in amplitude by the avalanche multiplication is observed, the width of the spectrum remains substantially unchanged at this frequency. Furthermore, the narrow line spectrum is obtained at two biases and thus no spurious effect was introduced in the demodulating process of the signal in time domain.



(a) (b)

(c) (d)

Fig.12 Oscilloscope traces of instantaneous noise under different biases at the same current of 80µA.Ver:2mV/div, Hor.:200µsec/div.

The photographs in Fig. 12 (a)-(d) show the instantaneous noise on an oscilloscope at the same photocurrent but different biases for a sample under test. It is apparent that the noise varies rapidly with applying bias even under the same current level.

5. Conclusion

Low-frequency (10-100) kHz shot noise due to photoinduced current where the noise is frequency-independent was measured and discussed of planar Mo/n-Si/Mo optical sensor structures proposed in this study. The noise ratio for these structures could change by two orders of magnitude, depending on the bias. The rapid increase in photocurrent at higher biases is attributed to the effect of avalanche multiplication. The linear photocurrent dependence of noise is seen to increase with bias towards the 'avalanche breakdown' of the diode which the magnitude of the corresponding noise are increases steeply. Furthermore: the opto response at low frequency range has been examined. It was observed that the spectra of the photoresponse consisted of the contributions of both the depleted and undepleted neutral regions.

6. Acknowledgement

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