Shot noise due to carrier generation in planar metal-semiconductor-metal optical sensors structures

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Abstract

Low frequency 3-100 kHz shot noise (white noise) emerging from photoinduced current in Mo/n-Si/Mo structures leaving undepleted region has been observed under different bias and optical intensity conditions. The measurements revealed that the current noise observed depends not only on the illumination intensity levels but also on bias voltage. The current noise observed is expressed as $S(\omega) = 2qI\Gamma^2$ and analyzed, where I and Γ^2 is the average current and noise factor, respectively. The measurements reveal that Γ^2 has strong bias dependence, lying $\Gamma^2 \sim 0.01$ to about unity corresponding to simple shot noise. Such experimental results are explained, stating that the reduction of crosscorrelation between drift and diffusion currents and autocorrelation of drift current component determining the level of noise occurs with decrease in SCR width bias-dependent. To explain the behavior of observed noise more properly, we propose, in addition to the mechanisms above, that the reduction in autocorrelation effect of each current component plays an important role to decrease the relevant noise to such extremely low levels.

Keywords: Metal-semiconductor-metal structure; Shot noise; Noise ratio; Low-frequency noise; Photocurrent

1. Introduction

The planar MSM structures and their operation principle for detecting optical quantities to be processed have been described. Since an MSM structure is treated as a photodetector, such structure is expected to be put at the front stage of the system concerned. Therefore, reminding us of the idea of Friis [1-2], the noise property of the MSM photodetector would be an important problem, resulting in the influence on the whole of the system. The noise in an electronic device is categorized mainly into three. They are shot noise, $1/f$ noise or Flicker noise and thermal noise or Johnson noise [3-4].

The frequency range where shot noise appears is most frequency region used for device operation but the region where carriers are transit-time-limited in the active region of the device [4-5]. The region transit-time-limited is usually situated at much higher frequencies such as GHz or THz order. Except for the transit-time-limited region, the spectrum distribution of shot noise is in general frequency independent or white and is proportional to the average current of the devices [6-8]. Flicker noise has the frequency dependence of the reciprocal of frequency, thus sometimes called $1/f$ noise. Therefore, the noise of this kind would be dominant at low frequencies, depending also upon the current flowing in the device. Thermal noise or Johnson noise is due to statistically random motion [12] of carriers thermally agitated in the device. The spectra of these three noises are illustrated in Fig. 1 schematically.

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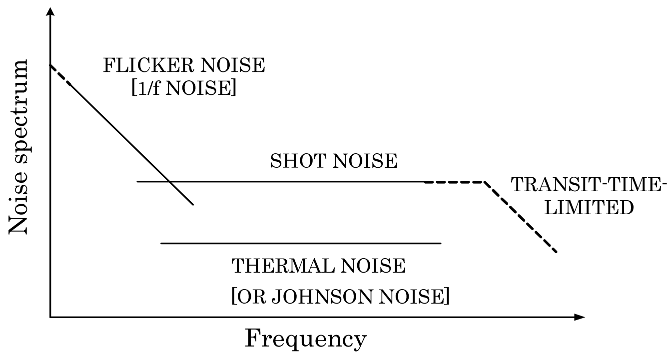

Fig. 1 Schematic of spectra of shot noise, Flicker noise and thermal noise.

When a two terminal semiconductor device is carrying an average (dc) current, the device inevitably exhibits so-called shot noise (white noise). 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).

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

which is called the full (or simple) shot noise. In case of practical devices, however, Eq.(1) is sometimes modified to fit the noise observed as

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

where Γ^2 is the noise ratio or the noise factor representing the ratio of the noise to full shot noise [2-3]. In case that the noise is affected by the transit-time of carriers, the noise ratio would be the function of frequency [1,5]. Thus, the noise ratio would be regarded as a kind of the noise measure of the device under consideration. The relation $\Gamma^2 = 1$ has generally been accepted in existing theories for two-terminal semiconductor devices such as photodiodes and photoconductors [13-14].

When a device is carrying an average current I and this current consists of n current components uncorrelated between any two current components, the resultant noise $S(\omega)$ at low frequencies is given as

$$S(\omega) = 2q\sum_{n=1}^{n} \Gamma_n^2 I_n = 2q(\Gamma_1^2 I_1 + \Gamma_2^2 I_2 + \ldots + \Gamma_n^2 I_n) \tag{3}$$

where Γ_n^2 is the noise ratio defined for the corresponding n-th current, I_n [3]. As is discussed so far [9,11], each noise ratio is expected to lie between 0.5 and 1.0 for the noise due to charge carrier generation in the semiconductor materials and devices. The case $\Gamma^2 = 0.5$ corresponds to the noise due to spatially uniform carrier generation in the midst of the active area as a limiting case [2]. $\Gamma^2 = 1.0$ represents the noise ratio exhibited by carriers traversing between the electrodes where carrier generation or carrier injection is taking place at either electrode.

From Wiener-Khintchine theorem [1-3], the current noise spectral density $S(\omega)$ at an angular frequency ω is expressed as

$$S(\omega) = 4\int_0^\infty \langle i^2(t)\rangle c(s)\cos(\omega s)ds \tag{4}$$

Thus, at low frequencies where $\cos(\omega s)$ is approximated to be unity and the noise spectrum is independent of frequencies, $S(\omega)$ reduces to the following relation,

$$S(\omega) \approx S(0) = 4\int_0^\infty \langle i^2(t)\rangle c(s))ds \qquad (5)$$

Here, $i(t)(t:\text{time})$ is the instantaneous current component due to a single diffusing carrier, $\langle i^2(t)\rangle$ is the average of $i^2(t)$, and $c(s)$ is the normalized autocorrelation function which will be introduced later in this chapter. If there is no noise reduction due to decay of the autocorrelation, the above equation reduces to full shot noise. Moreover, supposing that the correlation function is given by [2]

$$c(s) = \exp(-s/\tau) \qquad (6)$$

where τ is the average lifetime, one can estimate roughly the ratio of the correlation time to the average diffusion time as follows.

2. Experimental

Experimental samples have the following feature. Molybdenum (Mo) was e-beam-evaporated onto an n-type silicon wafer, whose resistivity is mainly $8-12\Omega\text{cm}$, and using photolithography and lift-off technique [11], the electrodes were completed. The thickness of the evaporated Mo film is approximately $(1-1.2)\times10^3$ Å. The cross-sectional view of the sample is shown in Fig 2. Metallized molybdenum film forms a Schottky barrier on silicon and acts as an electrode as well [8]. The shape of the electrode is a simple square of size $3\times3\ \text{mm}^2$ as shown below. The barrier height of independent Schottky barriers lies between 0.57 eV and 0.67 eV and coincides with those reported earlier [6-11]. The electrode separation is 20 μm. When a bias voltage is applied between the anode and cathode, a part of the region between both electrodes nearer to the cathode (negatively biased electrode) would be depleted further corresponding to the magnitude of the applied bias. The finger separation is larger than the sum of the depleted region width within the voltage region examined and the diffusion length of minority carriers optically generated in the undepleted region. This condition is essential for the present devices to furnish the voltage controllability of photocurrent as mentioned before.

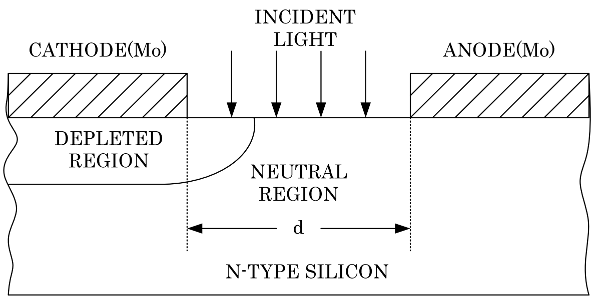

Fig 2. Crosssectional view of a planar MSM structure

The noise measurements were performed using the system pictured in Fig 3. The frequency range of the noise measurements is from 3kHz to 100kHz. 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 (Ithaco 1201) and finally detected by a lock-in voltmeter (NF 5560). To check the system characteristic, a white noise generator (Ando GRN-2) 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.

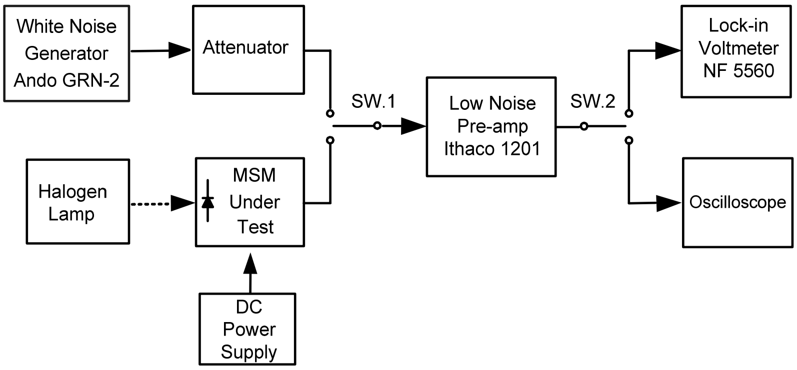

Fig 3. Block diagram of noise measurement system. For calibration of the system and noise observation in time domain, sw.1 and sw.2 are switched, respectively.

3. Results and discussion

In Fig. 4, the typical photocurrent I_P versus applied voltage V plots by solid lines for a sample having 20μm-separated electrodes are shown at various levels of optical illumination in log-log scale. With increasing the bias voltage, the width of depleted region is an increasing function of the lateral spreading at the front surface. The width of the depleted region within the bias range examined is to be larger than the penetration length of the visible light which is given by the reciprocal of the absorption coefficient.

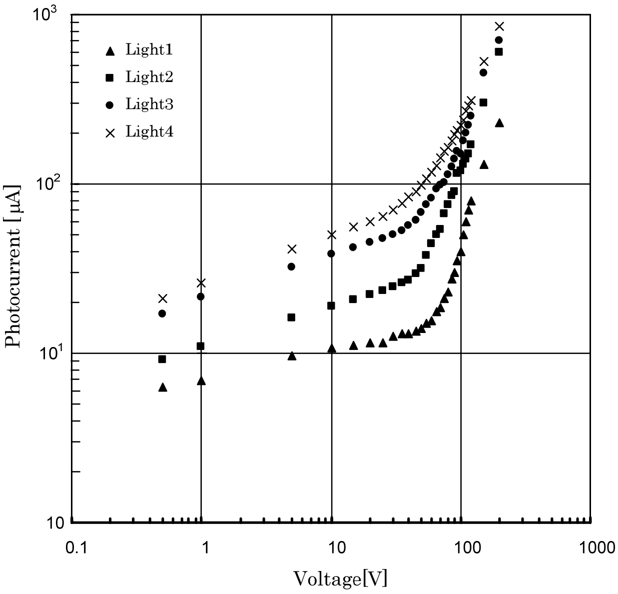

Fig 4. Photocurrent-voltage characteristics of a Mo/n-Si/Mo structure having 20 μm electrode separation

Figure 5 shows the noise-photocurrent relationship in log-log scale at 10kHz for a sample, taking bias voltage as a parameter. Here, the noise and the photocurrent were obtained by subtracting the noise in the dark from the noise as measured and by subtracting the corresponding dark current at the same bias from the device current as measured, respectively. From these noise measurements, one finds that the plots are straight, resulting in coincidence with the relationship predicted from Eqs.(1) and (2). The measurements revealed that the current noise observed depends not only on the illumination intensity levels but also on bias voltage [15-16].

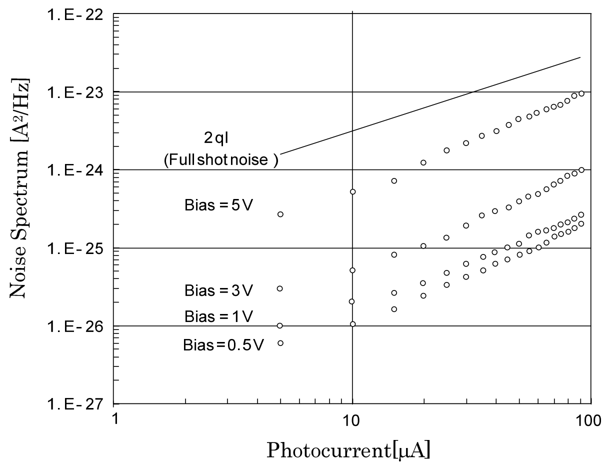

Fig.5 Shot noise spectra versus photocurrent of a Mo/n-Si/Mo structure at 10kHz, taking the bias voltage as a parameter.

When the bias voltage increases, the corresponding noise is also elevated, and asymptotically approach full shot noise given by the solid line calculated from Eq.(1). That is, the noise ratio defined in Eq.(2) is an increasing function of bias voltage, whilst the relation expressed by Eq.(2) is maintained within these plots. When the bias is at 0.5V, the corresponding noise ratio lies around two orders of magnitude lower than that of full shot noise. This extremely small noise ratio is not completely explained by the consideration of the planar metal-semiconductor-metal (MSM) structure, where spatially uniform carrier generation is taking place [2,11].

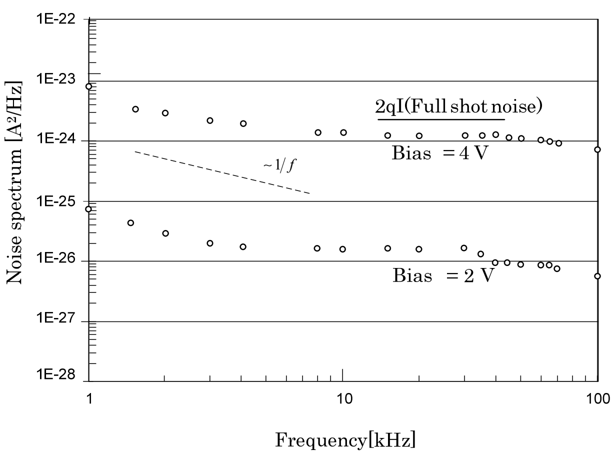

Fig. 6 Noise spectra of a 20 μm separated electrode sample at two different bias of 2V and 4V at a current of 6-7 μA. At lower frequencies, flicker noise is dominant.

Measurements for noise spectra at low frequencies were performed. The frequency range examined is from 10kHz to 100kHz, where the noise spectral density is independent of the frequency. In lower frequency region than 10kHz, flicker noise is dominant as shown in Fig. 6 for 20μm-separated electrode sample, where broken line shows the slope of flicker noise and solid line shows full shot noise respectively to guide the eye.

According to the existing theory of the autocorrelation function for semiconductor materials [1-3], the correlation function $c(s)$ represents the number of carriers present at the instant t that still contribute to the current fluctuation I at the instant $(t+s)$. In a semiconductor, carriers may be taken out of circulation not only by arriving at the electrode on one-side, but also by recombination or trapping inside the material. Consequently,

$$c(s) = (1 - s/\tau_2)\exp(-s/\tau_1) \quad for \quad s < \tau_2 \tag{7}$$

and

$$c(s) = 0 \quad for \quad s > \tau_2 \tag{8}$$

Here τ_1 is the average free time of the carriers between their generation by incident light and subsequent recombination; τ_2 is the average drift or diffusion time of the carriers. The autocorrelation function reduces to $c(s) = (1 - s/\tau_2)$ if $\tau_2 << \tau_1$; all carriers then enter the active area at electrode on one side and leave the electrode on the other side of the area. Therefore, the full shot noise formula (1) should be expected; this case applies if the active area is very narrow.

If the electric field E is applied, a drift velocity is superimposed on the random motion of electrons; this give rise to shot effect within semiconducting material between the electrodes. This current fluctuation is due to the drift of the electron in the field and even after collision the electrons drift again in similar way until the electrons are captured by positive ions or recombination. This condition means that most electrons taking part in the conduction are liberated inside the semiconductor and are captured again before they arrive at the positive electrode. Under such condition, $\tau_1 << \tau_2$ and thus the autocorrelation function reduces to

$$c(s) = \exp(-s/\tau_1) \tag{9}$$

Few carriers then enter the area at one side or leave it at other side; instead, most of them are created inside the area and captured again. In this case, the noise intensity is much less than the full shot noise intensity, $2qI$. Let us consider the case that the applied bias is relatively high such as 4V in Fig.6. It can presumably be assumed that the internal electric field becomes higher than under the lower biases as the numerical simulation predicts [3-5]. Under this condition, the autocorrelation function for the photogenerated carriers in the depleted region is relatively large, although the autocorrelation function coefficient for the carriers generated in the undepleted region is small. This could be the reason why the noise ratio lies at higher levels at a bias of 4V for the present structure. In order to explain such small noise ratio as observed, such a noise is attributed to the small relevant autocorrelation function of the currents at lower biases [8,9,11]. That is, making use of Eq. 9), very small autocorrelation function $c(s)$ for the structure would be expected since the internal field in the depleted region is low enough to satisfy the relation $\tau_1 << \tau_2$.

Therefore, an extremely small autocorrelation function for the drift current can occur, while the autocorrelation coefficient for the diffusion current remains unchanged at low level.

The photographs in Fig. 7 (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.

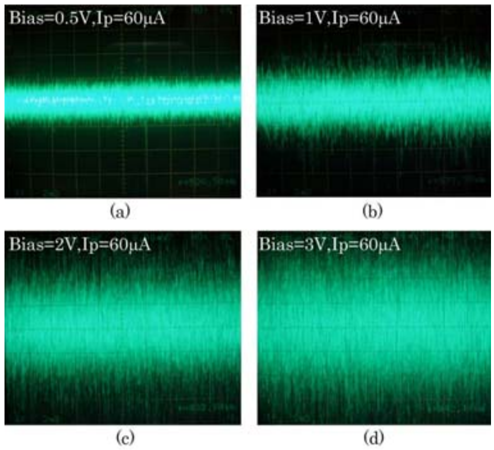

Fig.7 Oscilloscope traces of instantaneous noise under different biases at the same current of 60μA. Ver.:2mV/div., Hor.:200μsec/div.

As mentioned in a two-terminal semiconductor device carrying an average (dc) current, the associated noise would be of full shot noise type. The qualitative explanation for these experimental results giving rise to such low levels of noise is as follows. Accordingly, the change of depletion width cannot give rise to the reduction of autocorrelation of carriers than expected in Mo-Si systems. This explanation is also consistent with the I_P-V characteristics given in Fig.8. In this figure, the increase in bias voltage does not contribute the increase in the photocurrent. This is the reason why the present sample show smaller bias dependence of the noise observed.

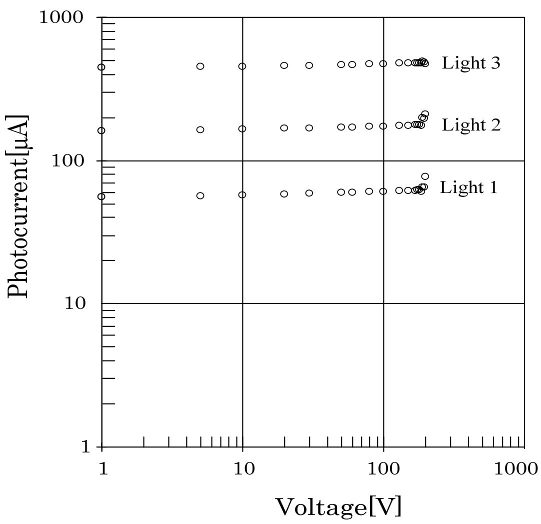

Fig. 8 Photocurrent-voltage (I_p-V) characteristics of a pin photodetector.

For comparison, the measurements revealed that the current noise depends not only on the illumination intensity levels as ordinal (not planar but vertical) photodetectors but also on bias voltages. The pin photodiode examined here, which consists of a lightly-doped or intrinsic region sandwiched between *p* and *n* regions, represents a better alternative to the simple p-n photodiode. This is because, at relatively low reverse biases, the intrinsic region is fully depleted and the total depletion region width including those from the *p* and *n* regions remains almost constant when the peak electric field inside the depletion region is increased [16-17].

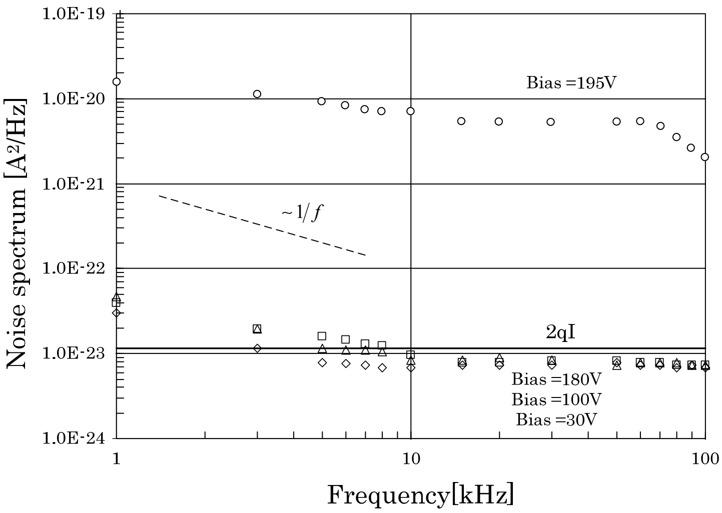

Fig. 9 Noise spectra of a commercial pin photodetector under different bias of 30V, 100V, 180V and 195V at the current 30 μA. At lower frequencies, flicker noise is dominant.

Figure 9, shows the measured noise spectra at photocurrent 30μA of the pin photodetector treated in Figs. when the applied bias is taken as a parameter. To compare the results, the typical photocurrent dependence of the noise for the pin photodiode is given in Fig.10.

The experimental results give rise to the noise ratio Γ^2 approximately between 0.84-0.86 as shown in Fig. 9. One also finds from the figure that the linear photocurrent dependence of noise is seen to increase with bias towards the ‘avalanche breakdown’ of the diode [14,16]. The magnitude of the corresponding noise increases steeply, to reach $9E^{-21}A^2/Hz$ at 195V.

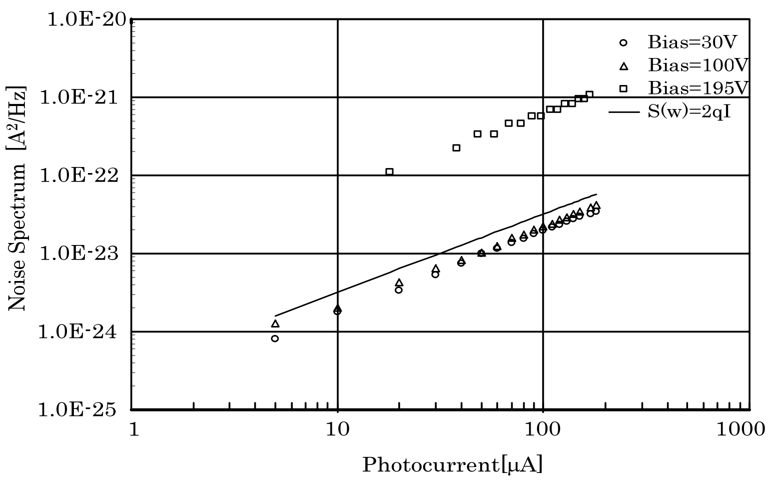

Fig. 10 Noise spectral density at 10 kHz versus photocurrent of the commercial pin photodiode, taking the bias voltage as a parameter.

In spite that the bias voltage increase to 180V, the noise spectra remains substantially in level. In Fig. 9 and 10, the level of noise for 195V bias jumps to much higher level. This must be attributed to the onset of avalanche breakdown which is inherently noisy process [15-17].

Under breakdown condition, the reverse current increases very sharply, and relatively large currents can flow with a little further increase in voltage [4,16]. Because of the carrier multiplication due to impact ionization, the current entering the depletion layer is multiplied by a factor, M, known as the multiplication factor, as it crosses the layer. Figure 9 and 10 strongly suggest that, according to McIntyre's theory [16], the steep increase in current and noise up to much higher level than near the breakdown voltage is due to impact ionization multiplication in the junction reverse-biased [17].

For reference, about the same sample appeared in Figs.9 and 10, Figs. 11(a)-(d) show the instantaneous noise in time domain on an oscilloscope at the same photocurrent but different biases, which are observed through the low-noise preamplifier. It is apparent that the magnitude of the noise does not increase with the increase in bias before breakdown starts despite of making the photocurrent fixed at about 30μA.

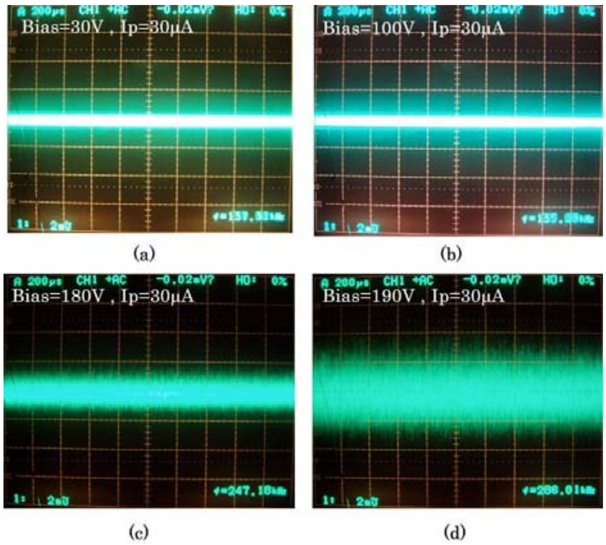

Fig.11 Oscilloscope traces of instantaneous noise of the pin photodetector treated in Figs.8-10 under different biases at the same current of 30μA. Ver.:2mV/Div., Hor.: 200 μs/Div.

4. Conclusion

The noise characteristics at low-frequency region ranging 10kHz-100 kHz, where the noise is frequency-independent, were measured of planar Mo/n-Si/Mo optical sensor structures under optical illumination. The current noise spectral density observed was found to be not only current-dependent but also bias-dependent. The noise ratio for these structures was lower than simple shot noise by two orders of magnitude under some cases, depending on the bias applied. These low-noise behaviors have been qualitatively explained and attributed to three mechanisms: (1) No crosscorrelation between the drift current due to carriers emerging from the depleted region and the diffusion current due to carriers emerging within the diffusion length from the boundary with the depleted region. (2) Spatially uniform carrier generation in both depleted and undepleted regions. (3) Small autocorrelation coefficient of the drift- and diffusion-currents coming from low internal field in accordance with small applying bias.

It can be mentioned that such low photoinduced shot noise of these structures is of much interest from the view point of the signal-to-noise (S/N) ratio of optical sensing structures.

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