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Non-Gaussian noise in quantum wells infrared photodetectors

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Abstract

Non-Gaussian dark current noise has been observed in quantum wells infrared photo detectors. The non-Gaussian component of the noise was ascribed to fluctuations of spatial distribution of electric field in the device. Non-Gaussian noise was found in both n- and p-type QWIPs, however, it was significantly less pronounce. In n-type devices non-Gaussian noise manifests itself only as randomly distributed excess current bursts. In p-type QWIPs the non-Gaussian noise takes form of bias dependent random telegraph-like fluctuations with a finite time of transition between the levels. The lifetime at both levels is Poisson distributed and the average lifetime, together with the level spacing, strongly depend on bias voltage. At low voltages the system stays predominantly in the low current level while at higher voltages the average lifetime of the high current level is longer. The transient time of passing between the states has been related to the charging time constant of the system determined by QWIP capacitance and contacts resistance.

Noise investigations are a useful tool for exploring physical mechanisms governing performance and reliability of semiconducting devices. The information contained in the noise is equivalent to the information, which can be obtained from dynamic response measurements when the concerned noise is Gaussian. However, for non-Gaussian fluctuations, the noise contains more physical information than the response measurements. In particular, just the mere fact of appearance of non-Gaussian fluctuations indicates that the noise cannot originate from a combined action of a large ensemble of elementary fluctuators, since according to the central limit theorem such noise should be Gaussian, even if the elementary fluctuators are not Gaussian. In mesoscopic systems, the non-Gaussian character of the noise is most commonly related to a limited small number of fluctuators in the system. In bigger samples, the non-Gaussianity is a signature of an action of single macroscopic fluctuators changing the state of the entire system on the length scale comparable with the system size.

Characterization of non-Gaussian noise requires measurements of higher order moments, beyond the standard two point correlations and power spectral density (PSD). Nevertheless, in many cases, just simple measurement of time traces of non-Gaussian events enables a powerful insight into the involved physics. The best example is the time domain analysis of extremely non-Gaussian random telegraph noise processes [1].

Noise in quantum well infrared photodetectors (QWIPs) was studied extensively in the last years [2–15]. Generation-recombination (GR) noise, closely related to the usual GR noise in classical photodetectors, [16] has been accepted as a dominant noise mechanism in QWIPs. In most of previously published papers each well of a QWIP structure was treated as a discreet extrinsic standard GR noise source. Within this approach some generic properties of QWIP‘s noise were established and relatively good agreement between the model and experimental results was achieved. For example, the model predicts a decrease of the dark current noise with increasing number of wells in the system, exactly as observed in the experiment [15].

A classical GR noise is characterized by frequency independent spectrum, up to a cut-off frequency located in the GHz range. However, GR noise in QWIPs should be low-pass filtered at much lower cut-off frequency related to the QWIP time constant RC. The time constant is

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determined by the contacts resistance and device capacitance [10,14,17]. The device dependent cut-off frequency corresponds to the inverse of the recharging time of depleted wells [14].

We have previously reported on the first experimental evidence of bias dependent non-Gaussian dark current noise in p-type QWIPs [18]. In the recent experiments, we have detected a similar phenomena in n-type QWIPs. In this paper, we discuss non-Gaussian dark current noise in both n- and p-type QWIPs and discuss plausible physical mechanisms responsible for such fluctuations.

N-type and p-type mesa QWIPs were fabricated on a (100) semi-insulating GaAs substrate. Both types of structures have a diameter of 200 μm and consist of five periods of 4.6 nm GaAs wells doped at 5×10^{17} cm^{-3} separated by 50 nm undoped AlGaAs 30% Al barriers. Top and bottom 500 nm width ohmic contacts areas were doped at 2×10^{18} cm^{-3} and separated by a 100 nm spacer of an undoped GaAs. Vacuum evaporated Ge/Au contacts for n-type and Zn/Au contact for p-type, were alloyed at 430 °C. The GaAs cap layer was grown at 650 °C, while all other layers at 750 °C.

All measurements reported in this paper were performed at liquid nitrogen temperature with the sample immersed directly in a liquid nitrogen bath. Special care was taken to eliminate parasitic noise contributions from ambient electromagnetic fields by extensive shielding and grounding arrangements. A commercial transimpedance current amplifier placed at room temperature at the top of the cryostat was used to amplify dark current fluctuations. The amplified signal was analyzed in time and frequency domain by a computer assisted dynamic signal analyzer. The system performance was checked by replacing a QWIP with a dummy sample of a resistor having the same resistance as the QWIP at a given temperature. In the range of experimental parameters, the system noise was found to contribute only a small addition to the thermal noise of a dummy resistor. In the actual noise measurements, the background noise was reduced in the data by measuring the noise at zero bias and subtracting it from the noise measured at each bias. This procedure helps clean the spectrum but does not eliminate the background completely as the impedance of the system is voltage dependent.

The power spectral density (PSD) of the dark current noise in a p-type QWIP and its evolution with changing positive bias voltage is illustrated in Fig. 1. Generally, as expected for GR noise, the low frequency spectral density increases with increasing bias. PSD at low frequencies is white, up to a clearly marked cut-off frequency above which the noise intensity decays to a high frequency plateau level. At intermediate bias voltages the PSD decays above the cut-off following the power law $S_i \sim 1/f^{\alpha}$ with $\alpha = 1$, while at other voltages α is closer to 1.5. The cut-off frequency is bias dependent and with the exception of the lowest bias point $V = 0.5$ V, increases monotonically with increasing bias. It should be noted that the spectral behavior illustrated in Fig. 1 is very similar to that reported

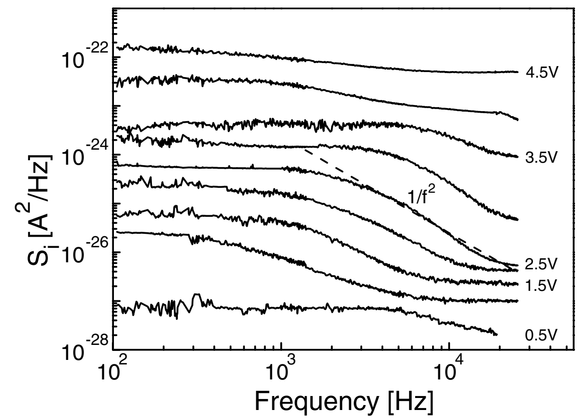

Fig. 1. Dark current noise spectrum of a p-type QWIP recorded at different positive voltages at 77 K.

recently for an n-type device, where the observed cut-off has been ascribed to recharging processes [14].

Bias dependence of the cut-off frequency (f_c) can be well fitted to the exponential growth law with distinct exponential factors in low and high voltage regimes, as shown in Fig. 2. At low voltages, between 1 and 2.5 V, f_c follows the relation $f_c(V) = f_{c0}\exp(\beta V)$ with $\beta = 0.6$, while at high frequencies the best fit is obtained for $\beta = 1.45$.

In order to get a better insight into the nature of the dark current fluctuations in our QWIPs we have performed measurements in time domain. Fig. 3 shows time domain records of dark current at different bias conditions together with the corresponding amplitude distributions. At low voltages, below −1 V, the amplitude of dark current fluctuations is low, not exceeding 3×10^{-10} A, and the distribution is Gaussian, see Fig. 3a. With increasing voltage the dark current increase is accompanied by increasing noise intensity. At intermediate voltage levels, around −2.5 V, current noise amplitude distributions become pronouncedly non-Gaussian, as illustrated in Fig. 3b, and can be well fitted by two Gaussians with distinct mean values and different variances. The current noise resembles

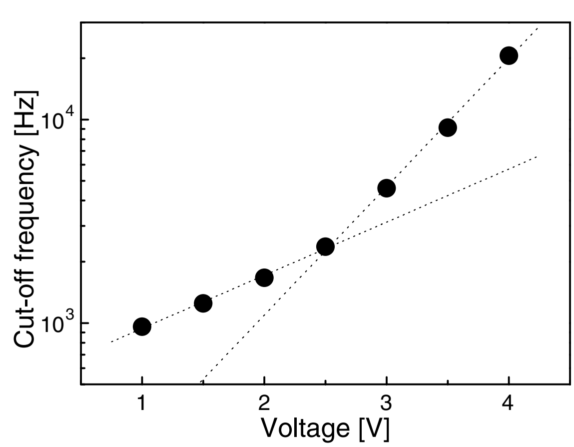

Fig. 2. Bias dependence of the cut-off frequency determined from the spectra shown in Fig. 1. The dashed lines are best fits to exponential increase $f_c(V) = f_{c0}\exp(\alpha V)$.

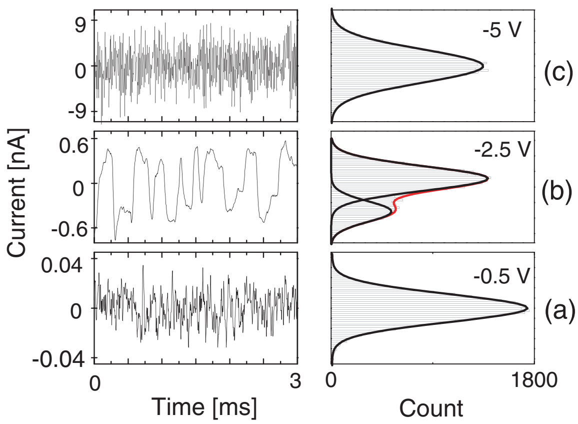

Fig. 3. Time traces of the dark current and corresponding noise amplitude distributions for different bias voltages at 77 K.

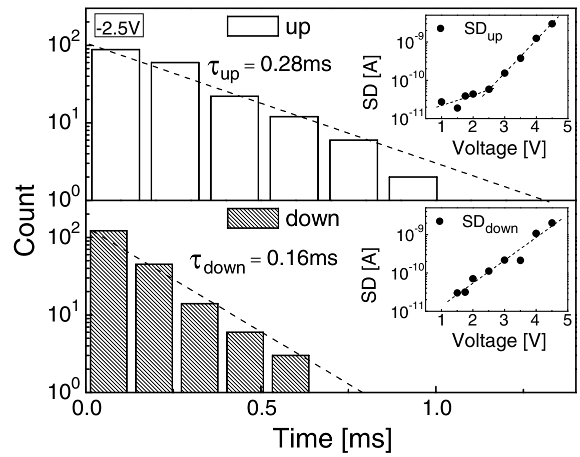

Fig. 4. Lifetime distribution of both the up and down state at −2.5 V. The lifetime of both states, follow the Poisson distribution. In the inset, the standard deviation (SD) of the up and down level are presented as a function of the voltage. The dashed lines are the best fits to the exponential decay function.

now a random two-level telegraph signal with Gaussian noise around each level. With further voltage increase the non-Gaussian character of the noise diminishes and, eventually, at voltages above −4.5 V the distribution returns again to be Gaussian, see Fig. 3c. Bias voltage at which non-Gaussian two-level behavior is most pronounced coincides with the voltage at which an abrupt change in the exponent fitting bias dependence of the cut-off frequency is seen in Fig. 2.

For positive voltages, as in previously discussed negative bias case, the non-Gaussian character of the noise becomes visible in the intermediate voltages between 1 V and 4.5 V. The two-level signal is most pronounced between 2.5 V and 3 V. The distribution returns to be Gaussian at voltages above 4.5 V.

When the dark current fluctuates around two distinct current levels one can ascribe each level to a different state of the system. Since the QWIP is biased with a constant voltage source, the higher current level of the telegraph-like signal, which will be referred to as the "up" level, corresponds to the low resistivity state of the device, while the lower level, which will be referred to as the "down" level, corresponds to the high resistivity state of a QWIP. Gaussian fluctuations around each level can be identified with the well-known GR noise. The GR component in the frequency range concerned in the experiment is frequency independent since the GR cut-off frequency is well beyond the bandwidth of our measuring setup.

A further proof for the random telegraph-like nature of dark current fluctuations was obtained from the analysis of lifetime distributions. As shown in Fig. 4, the lifetimes of both levels are Poisson distributed. The average lifetime of the up state, calculated from the exponential decay constant, $\tau_{up} = 0.28$ ms, is longer than the average lifetime of the down state $\tau_{dn} = 0.15$ ms meaning that at this bias voltage −2.5 V the system stays predominately in the low resistivity up state.

Standard deviation (SD) of the noise at each level is shown in the insets to Fig. 4. SD at both levels increases exponentially with increasing bias. The exponent $\beta = 1.3$ V, and is close to half of the exponent fitting the dark current voltage (*I*–*V*) characteristic of our QWIP. The *I*–*V* growth exponent equals 2.5 V, as seen in Fig. 5.

The above findings enable us to better understand the dark current noise PSD from Fig. 1. The PSD of the pure random telegraph noise is known to be Lorentzian with the cut-off determined by the average lifetimes in both RTN states $f_c = 1/\tau_{up} + 1/\tau_{dn}$. The form of time traces shown in Fig. 3 strongly suggests that bias dependent low frequency spectral cut-off should be related to the corner frequency f_c of the RTN-like noise component. Therefore, the PSD should decay as f^{-2} above the cut-off frequency, what is indeed observed at bias enhancing the non-Gaussian character of the noise.

Time domain analysis reveals that the average lifetime of each telegraph state changes monotonically with increasing bias, with a clear tendency to stay in the up state at high voltages. Bias dependence of the non-Gaussian current

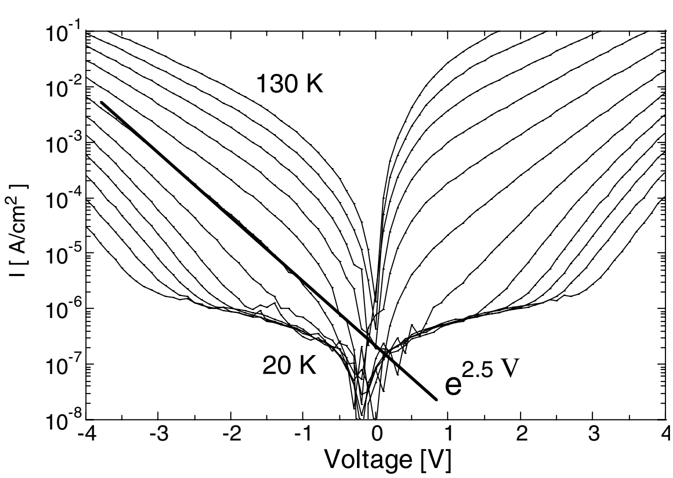

Fig. 5. *I*–*V* curve of the dark current as measured for different temperatures. At 80 K the dark current is growing with 2.5 V exponent.

noise component can be characterized by defining the duty cycle $D = \tau_{up}/(\tau_{up} + \tau_{dn})$. The areas under Gaussian distributions around the levels, A, determine the total time spend by a system in a given level, time which is proportional to the level average lifetime. Duty cycle D can be thus experimentally determined by finding the areas A_{up} and A_{dn} from a two-Gaussian fit to the amplitude distributions of the current and calculating duty cycle as $D(V) = A_{up}(V)/[A_{up}(V) + A_{dn}(V)]$. Duty cycle evolution with the bias voltage is illustrated in Fig. 5. Indeed, at low voltages the system stays predominantly in the high resistivity down state and at high voltages, predominantly in the low resistivity up state. At voltages around −2.5 V the telegraph-like signal becomes symmetric and the average life times in both states are equal.

Since the cut-off frequency of the two-level RTN is mostly determined by the shorter of the average lifetimes it can be postulated in the low voltage regime that the cut-off is dominated by the low resistivity state average life, τ_{up}, while at high voltages by the average lifetime in the high resistivity state τ_{dn}. Assuming that the average lifetimes preserve their voltage dependence in the entire bias range and extrapolating the low and high voltage evolutions of the cut-off frequency, one can determine the duty cycle in an alternatively way. As shown in Fig. 6, the alternative approach allows for a good estimation of the duty cycle at voltages close to 2.5 V. This approach is correct at voltages close to that rendering a symmetric RTN, and start to be inaccurate far from the symmetry point, as marked by dashed lines in Fig. 6. The duty cycle calculated from the cut-off frequency around −2.5 V point, coincides within the measurement errors to the duty cycle established from the time domain analysis.

Considering the cut-off frequency as related to τ_{up} and τ_{dn} one can ascribe distinct exponents in the cut-off frequency bias dependence to different average lifetime dominating the cut-off at high and low voltages. The break down voltage of 2.5 V gives the exact bias point at which RTN is symmetric, $\tau_{up} = \tau_{dn}$, and the influence of both lifetimes is identical.

The non-Gaussian character of the noise prevents one from drawing decisive conclusion about the nature of the noise from the measurements of the PSD only. In principle, higher moments, beyond the 2-point correlations should be measured and analyzed. Nevertheless, the results of the time domain measurements allow us to conclude that the low frequency cut-off can be attributed to two bias dependent average life times, τ_{up} and τ_{dn}, in two distinct states of the system rather than to a single time constant of the recharging process, as suggested in the literature [10,14].

Average dark current difference between two levels, i.e. the spacing or the RTN amplitude, also changes with the voltage as shown in Fig. 7. Again, −2.5 V bias turns to be a crossing point. Below that point only a small change in the level spacing can be seen, while above that point the distance between up and down level increases exponentially. At this crossing point, two solutions to the current continuity equation seems to be possible. One possible solution in which the tunneling process is small and the resistance is large. While in the other solution, the tunneling process for the emitter and wells become dominant giving low resistance state.

The RTN amplitude along with the average lifetimes determines the magnitude of the RTN noise, which, in turn, determines the level of the low frequency plateau. Since The contribution of the RTN-like non-Gaussian component to the total spectrum can be evaluated as a difference between the high and low frequency spectral plateau reflecting the intensity of the Gaussian GR noise component. It can be seen in Fig. 7 that the non-Gaussian component increases almost exponentially with increasing bias. However, since the GR component also increases with voltage, the best measure of the relative importance of non-Gaussian noise component is the ratio between the noise levels at two plateaus. In this ratio, shown in Fig. 7, a clear peak is seen at the bias voltage of 2.5 V at which two

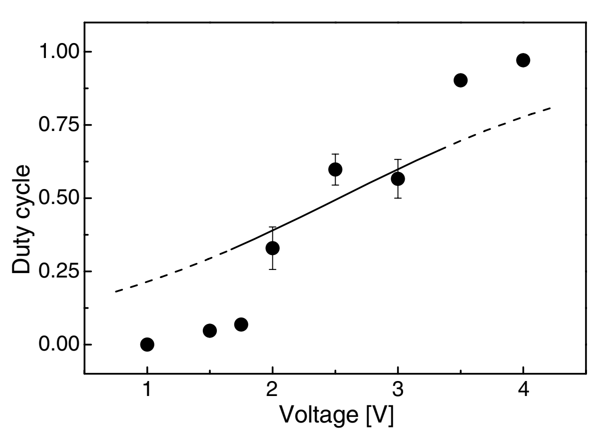

Fig. 6. Duty cycle of the dark current fluctuations. Full symbols represent data obtained from the amplitude distributions. Lines represent duty cycle evaluated from the cut-off frequency. Solid line is drawn in the voltage range where the assumptions of the two-level model apply, see text for details.

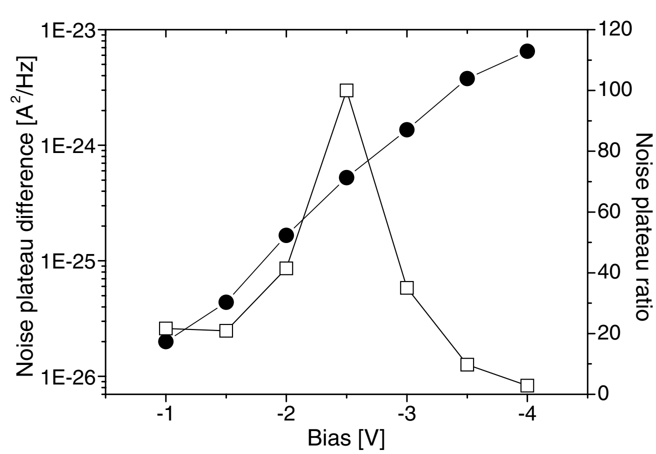

Fig. 7. Bias dependence of the RTN amplitude (solid circles) and the ratio between RTN plateau and GR plateau levels (open squares).

average lifetimes on distinct levels are equal. We expect that this characteristic bias is device dependent and would change from QWIP to QWIP depending on the doping, shape and size of wells and associated barriers, properties of the emitter, and the numbers of wells.

Voltage distribution in the QWIPs is a complicated function, strongly influenced by the number of wells, bias level, and temperature [19–22]. At equilibrium, for a given dc voltage bias, a constant current flows through the device. This current is proportional to the capture probability. If this probability is not monotonic at some voltages the distribution can be metastable [21] and switch between two different forms corresponding to two different states of a QWIP, see Fig. 8. A non-monotonic capture probability has been already measured before and few theoretical works attribute it to tunneling or inter-valley scattering [14,22,23]. Moreover non-uniform electric field distribution was already invoked in the past in order to explain deviation of noise measurements from the simple generation recombination noise theorem [24,25]. We assume that at a certain bias, two metastable voltage distributions can exist. One metastable state will have high resistance and low tunneling probability, Fig. 8a, while the other will be characterized by low resistance and high tunneling probability, Fig. 8b. The trigger for transition between metastable states is given by the recharging process which also controls the time of transition between the states. The transient time, which in our QWIP is in the order of few microseconds, does not depend on the direction of transition between "down" and "up" states. In this scenario, the distribution of electric field changes almost instantaneously, while the current responds within a RC transient time. At low voltages, the capture probability is close to one and, accordingly, the distance between two adjacent wells determines the relevant RC. At high voltages, the capture probability is low and, consequently, the RC should be calculated over the entire distance between the emitter and collector.

We expect that two discreet solutions would not appear in all p-QWIP systems since in most cases one will not get two meta-stable solutions to the continuity equation. Nevertheless the p-type telegraphic noise is very strong. In our opinion changes in the capture probability may be enhanced by different tunneling behavior of the light (LH) and heavy holes (HH) in a QWIP. For the p-type QWIPs studied in this work at 77 K the HH Fermi distribution population is 40 times larger than the LH population. On the other hand, due to LH smaller effective mass and lower tunneling barrier (Fig. 8) the probability for LH tunneling is higher. Thus, the LH will depopulate faster than the HH if the thermal equilibrium is not achieved. As the amplitude of the two level fluctuations is two orders of magnitude smaller then total dark current, LH population

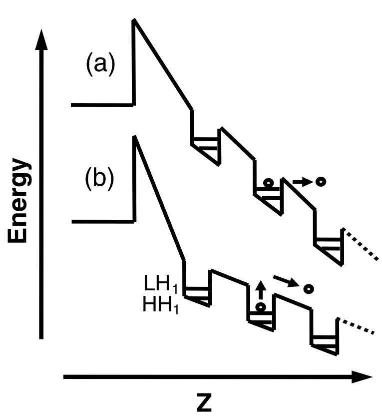

Fig. 8. Emitter well collector system with two different voltage distributions. Tunneling, Inter-valley transitions, or scattering could give two solutions to the continuity equations each with a different voltage distribution. (a) Is presenting the solution where high voltage is falling on the wells creating a larger dark current and strong tunneling between wells. In (b) the voltage falling on the wells is smaller and accordingly the dark current will be smaller.

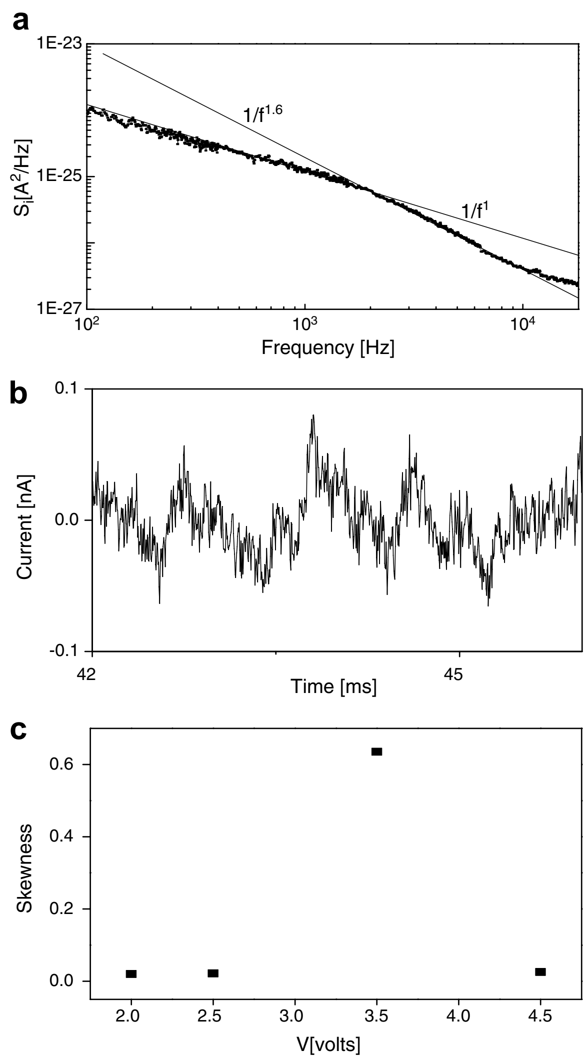

Fig. 9. Spectrum (a) and time trace (b) of the dark current of an n-type QWIP under voltage of 3.5 V at 77 K. In this voltage additional non-Gaussian noise is seen in the n-type QWIP. In Fig. 8c, the skewness of the dark current noise distribution is seen showing a peak at 3.5 V.

may provide a plausible reason for enhancement of the telegraphic switchings (see Fig. 9).

Non-Gaussian dark current noise at intermediate bias, voltages between 2 V and 4.5 V, has been also observed in an n-type QWIP, as illustrated in Fig. 8 showing the power spectral density (PSD), time domain record, and an amplitude distribution of a n-type QWIP dark current noise. Clearly the non-Gaussian features in the n-type QWIPs noise are much less pronounced then in the p-QWIPs. The amplitude distribution is a skewed Gaussian with the bias dependent skewness reaching the maximum around 3.5 V. Power spectral density of n-type QWIP non-Gaussian dark current noise decreases with increasing frequency following the power law $P \sim 1/f^{1.6}$, in apparent similarity to power spectra of crackling noise seen in other systems [26,27].

In summary, we have observed the non-Gaussian noise in both n-type and p-type QWIPs. The noise was significantly more pronounced in the p-type QWIPs where clear random telegraph-like noise was seen. The noise is attributed to two solutions of the continuity equation, which create two metastable voltage distributions corresponding to a high resistivity state with low current and a low resistive state with high current and associated characteristic bias dependent lifetimes. The switching time between the two states is controlled by the capacitance of the system. Increasing of the number of wells in a QWIP wells favors a constant capture probability and reduces the possibility of appearance of non-Gaussian current fluctuations in the device.

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