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Measurements of non-Gaussian noise in quantum wells

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Gaussian generation-recombination is accepted to be a dominant mechanism of current noise source in quantum well systems biased by electric field normal to the layers. We have found pronouncedly non-Gaussian excess current noise in *n*-type and *p*-type multiple quantum wells. The non-Gaussian noise has been attributed to metastable spatial configurations of electric field. The metastability likely originates from negative differential conductance caused by intervalley scattering in *n*-type wells and heavy and light holes tunneling in *p*-type wells. At a constant bias, the quantum well system randomly switches between a high resistivity state with low current flow and low resistive state with high current flow. The non-Gaussianity of the noise is more pronounced in *p*-type wells where the time traces of current fluctuations resemble closely a two-level random telegraph signal, which has not been straightforwardly observed in *n*-type wells. The non-Gaussian character of the noise in *n*-type systems has been revealed by measurements of nonzero skewness of the amplitude distributions. The difference between noise properties of *n*- and *p*-type systems has been attributed to small capture probability of electrons in *n*-type wells, as opposed to very high capture probability of holes in *p*-type wells. As a consequence, the noise of any *p*-type multiwell system is dominated by fluctuations of a single well, while in the *n*-type the noise appears as a superposition of many fluctuators associated with individual wells.

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I. INTRODUCTION

Noise is frequently regarded only as an annoying nuisance disturbing the experiment. In reality, noise measurements can provide a unique insight into the dynamics of the investigated physical system.[1] Noise in quantum wells (QWs) and, in particular, in quantum well infrared photodetectors (QWIPs) was extensively studied in the last years.[2–5] Although the noise measurements were primarily aimed at a practical goal of optimization of the signal-to-noise ratio in QWIP devices, they have also significantly contributed to our understanding of transport processes in QW systems. It is now generally accepted that generation-recombination (GR) noise constitutes the dominant source of current fluctuations in QWs.[6,7] In practice, QWs are always biased with a voltage source. At very low voltages, the current noise in QWs arises from trapping and detrapping of charge carriers from bound states.[8] At moderate and low bias voltages, the bias dependent GR noise prevails.[9–11] At very high bias voltages, $1/f$ noise, associated with the action of electronic defects in QW systems, appears and becomes most pronounced at low frequencies.

A simple relation based on considerations of statistical fluctuations of the number of charge carriers due to their emission and capture by the wells connects the dark current and the power spectral density (PSD) of the GR noise,[4]

$$S_i(V) = 4q\bar{I}g\left(1 - \frac{P_c}{2}\right), \tag{1}$$

where g is the gain, defined as a probability that a charge carrier reaches the collector, q is the electron charge, $\bar{I}$ is the dc current in the system, and P_c is the probability of capturing a carrier from the continuum to a QW. In deriving Eq. (1), each well was treated as a discrete independent source of GR noise. Relation (1) was the subject of controversial discussions over the years.[2–5]

The power spectral density of GR noise has a Lorentzian form. PSD is frequency independent at low frequencies, up to a cutoff frequency located in the GHz range. Above the cutoff, the PSD decays as $1/f^2$.[12]

Recently, fast and slow noise components of the current fluctuations, manifesting themselves as two plateaus in the PSD of the current noise, were found in quantum wells.[13,14] The plateau at higher frequencies originates from a conventional GR mechanism, while the low frequency plateau is considered to be a signature of an excess noise mechanism.[14] Alternatively, the time constant related to the recharging process of depleted QWIP wells has been claimed to be responsible for additional low frequency cutoff in the GR noise spectra.[13] The time constant of the recharging process is controlled by the QWIP resistance R and capacitance C. In a typical QWIP, the time constant is of the order of 10^{-4} s. Since the low frequency plateau in the noise PSD appears at frequencies coinciding with the typical operating frequency range of practical QWIPs, the excess noise may significantly deteriorate the performance of QWIP devices. Therefore, understanding of origins and mechanisms of excess noise becomes an important issue also from a practical point of view.

Important information about the physical nature of the excess noise was obtained in our first experiments when we have determined that in *p*-type quantum wells the excess noise has a non-Gaussian character.[14] Consistent with the central limit theorem, the classical generation-recombination noise originating from an action of many elementary fluctuators should be characterized by a Gaussian amplitude distribution.[4,12] Proper characterization of non-Gaussian noise requires measurements and analysis of higher moments beyond standard two-point correlations. Nevertheless, just the mere appearance of non-Gaussian fluctuations already proves that the excess noise cannot be produced by a combined action of many fluctuators.[15] The noise generated by an assembly of fluctuators should be Gaussian, even if the elementary fluctuations are not Gaussian. In mesoscopic systems, the non-Gaussian character of the noise is most commonly related to a limited small number of active fluctuators in the system. In larger samples, the non-Gaussianity of the noise is a signature of an action of a single or just a handful of elementary macroscopic fluctuators influencing system properties on a length scale comparable with the system size.[15,16] The non-Gausssian behavior of the excess noise indicates therefore that a new physical mechanism, beyond the well known GR noise, dominates current noise in quantum wells.

The work was motivated by our first experiments in which non-Gaussian noise in *p*-type wells was initially observed.[14] In this paper, we characterize in detail noise properties of both *p*- and *n*-type quantum wells and find the pronounced non-Gaussian current at moderate bias voltages in both types of QW. We interpret the results in terms of switching between metastable electric field distributions in the investigated systems. Even if the non-Gaussian current noise was found to be always much more pronounced in *p*-type wells, our results prove that additional noise source beyond the standard GR noise dominates noise properties of both *n*- and *p*-type QWIPs at moderate bias.

II. EXPERIMENT

Mesa QWs of *n* and *p* type were grown by metal-organic chemical-vapor deposition on (100) semi-insulating GaAs substrates. 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. The areas under 500 nm width top and bottom Ohmic contacts are doped at 2×10^{18} cm^{-3} and are separated by a 100 nm spacer of undoped GaAs. The GaAs cap layer was grown at 650 °C, while all the other layers were shown at 750 °C. Vacuum evaporated Ge/Au contacts for *n* type and Zn/Au contact for *p* type were alloyed at 430 °C.

All measurements reported in this paper were performed exclusively at liquid nitrogen temperature, with the samples 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. The sample was dc voltage biased by a high capacity battery. The resulting current was delivered to the input circuit of a homemade transimpedance current amplifier placed at the top of the cryostat at room temperature. The amplified current signal was analyzed in time and frequency domain by a computer assisted dynamic signal analyzer. The performance of the entire measuring system was checked by replacing a QWIP with a dummy resistor having the same resistance as the QWIP at a given temperature. The resistor and system noise were subtracted from the total noise for each voltage and temperature.

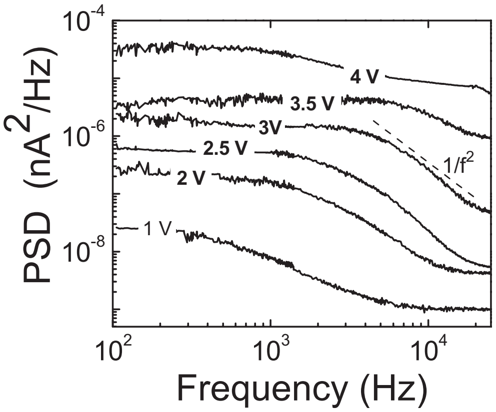

FIG. 1. Power spectral density of current noise in a *p*-type QW system under dark conditions for different bias voltages.

III. RESULTS

The measurements reported in this paper were performed with samples maintained in liquid nitrogen at 77 K. In this context, the term "dark conditions" will mean that the sample is exposed to the radiation of thermal surroundings of 77 K. Alternatively, the samples were exposed to the external blackbody radiation of 300 and 1000 K.

A. Noise spectra

Power spectral density of the dark current noise in *p*-type QWs recorded at various positive voltages is shown in Fig. 1. The noise spectrum is frequency independent up to a clearly marked cutoff frequency. At frequencies above the cutoff, the PSD of the current noise decays to yet another high frequency plateau. At intermediate voltages, where the excess noise is most pronounced, the decay above the cutoff is approximately proportional to f^{-2}.

The bias dependence of dark current noise in *n*-type QWs is illustrated in Fig. 2. The fastest decay of the PSD is seen at −2.2 V, where PSD decays above the cutoff frequency as $f^{-1.5}$. In general, the decay rates and differences between the high and low frequency plateaus in *n*-type QWs are significantly smaller than in *p*-type QWs.

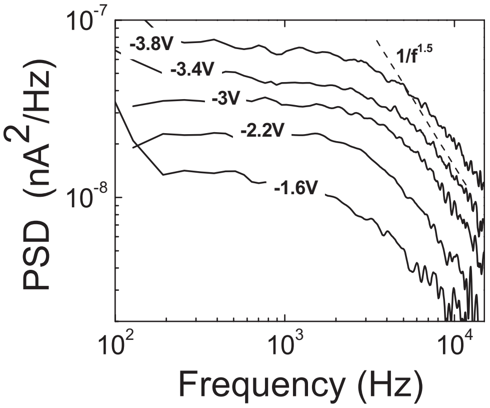

FIG. 2. Power spectral density of current noise in *n*-type QW system at 77 K.

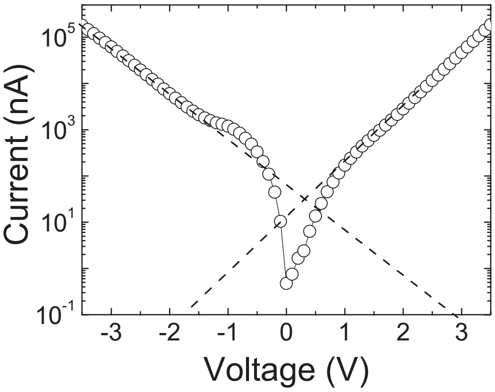

FIG. 3. Dark current of a p-type QW system as a function of the bias voltage. The dashed line represents the best fit to Eq. (2).

B. *I-V* characteristics

P-type QWIPs are characterized by very high capture probability and, consequently, by very low gain. In the n-type QWIPs, the capture probability is lower than in the p-type devices and, as a result, tunneling is less crucial. Since the n-type QWs have higher gain, practical devices are usually based on n-doped systems.

An example of typical *I-V* characteristics of a p-type QW system under dark conditions (i.e., exposed to the background radiation of 77 K) is shown in Fig. 3. At high voltages, the *I-V* curves can be well fitted to the exponential growth law,

$$I = I_0 \exp(\alpha|V|), \tag{2}$$

with exponent α=2.5 V^{-1} at the positive voltage branch and α=1.8 V^{-1} at the negative one. At low voltages, the curve is asymmetric and deviates from a purely exponential behavior. Moreover, a clear bump is seen in negative voltages around −1.2 V.

Typical *I-V* characteristics of an n-type well system under dark conditions and under illumination by 300 K background and by 1000 K blackbody radiation are shown in Fig. 4. Similar to p-type QWs, current in n-type QWs increases exponentially with increasing voltage. Under dark conditions, the exponential fit to Eq. (2) α=1.2 V^{-1} for negative voltages $|V|>3.5$ V. In the bias range 2 V$<|V|<$3.2 V, the exponent is approximately constant and takes a value of $\alpha \approx 0.7$ V^{-1}. At intermediate voltages, *I-V* characteristics of n-type QWs also deviate from a purely exponential behavior. Moreover, in n-type QWs, a pronounced current plateau appears in the *I-V* curves at intermediate voltages under 1000 K blackbody illumination. Deviations from the exponential behavior of the *I-V* characteristics in n-type quantum wells have been previously associated with gain changes, tunneling effects, and appearance of negative differential resistance.[17,18]

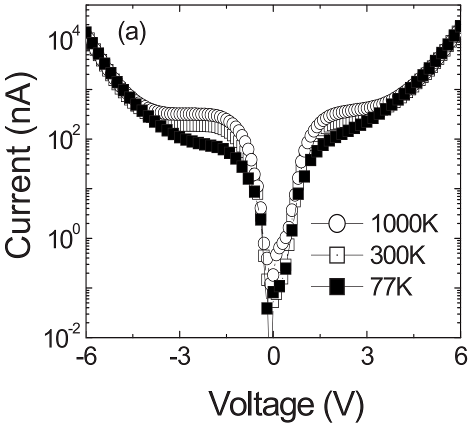

FIG. 4. *I-V* characteristics of n-type QWs at 77 K illuminated by 77, 300, and 1000 K radiation.

C. Statistical analysis of current fluctuations in time domain

Already, our first experiments have shown that the low frequency excess current noise has a non-Gaussian character.[14] For the Gaussian noise, all higher order time correlation functions and any of their Fourier relatives are fully determined by two-point correlation and corresponding PSD functions. Therefore, all available information about the process is obtainable from the PSD. A proper analysis of non-Gaussian fluctuations requires a determination of higher order statistics. Accordingly, a correct proof of the non-Gaussian character of the noise should come from appropriate statistical tests involving measurements of higher moments. However, the non-Gaussian character of the excess noise in p-type QWs is so pronounced that it can be asserted directly from the time records of the fluctuating current, even without performing proper statistical tests.

1. Random telegraph noise

It follows from Figs. 1 and 2 that with increasing bias, the low frequency noise increases above the expected GR high frequency plateau level. Nevertheless, at very low voltages, the excess noise in QWs is still very weak and the distribution of the time domain dark current fluctuations appears as Gaussian. In p-type wells at intermediate voltages, at which the *I-V* curves strongly deviate from the exponential behavior, the distribution of the current fluctuations becomes pronouncedly non-Gaussian.[14] In this bias range time traces of the p-type current noise resemble closely the two-level random telegraph noise (RTN).[19] The experimental amplitude distribution of the current noise can be fitted with two Gaussian distributions, each centered at the corresponding RTN level, as shown in Fig. 5. Here, the RTN *up* state corresponds to a high current level, while the *down* RTN state to a low current level. Since the sample is biased with a constant voltage, transitions from high to low current state are, in fact, transitions from low to high resistance state of the QW system. With further bias increase, the relative difference between the excess noise level and the GR plateau level in the measured PSDs diminishes and the non-Gaussian character of the noise becomes less visible. Eventually, at high bias voltages the noise amplitude distribution returns to be again undistinguishable from the Gaussian one.

The two-level fluctuations of the dark current differ from the canonical RTN noise by the fact that in the observed time traces, the time of transition between the levels (t

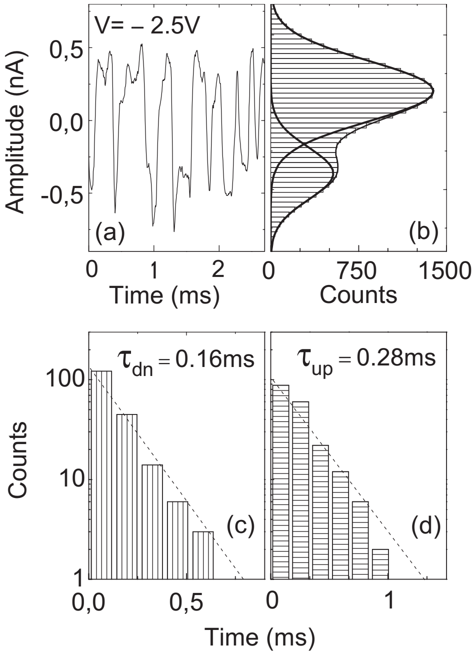

FIG. 5. (a) Real time records of dark current fluctuations at $V=-2.5$ V for a p-type QW system. (b) Amplitude distribution in the record shown in (a). The lines represent the best fit to two overlapping Gaussian distributions. Lifetime distribution of the (c) *down* state and (d) *up* state of the RTN-like signal from panel (a). The dashed lines are fits to the Poisson distribution.

~ 0.05 ms) is not negligibly short with respect to the lifetime of the system in each level. Nevertheless, as in the classical RTN signal, the lifetimes at both levels of the current noise were found to be Poisson distributed, as shown in Fig. 5(b). The average lifetime in each state can be obtained by determining the constant of the exponential decay of the experimental time distributions (yielding the same result as by averaging over the measured lifetimes). For example, thus determined average lifetime of the up state at -2.5 V is $\tau_{up}=0.28$ ms, which is longer than the average lifetime of the down state $\tau_{dn}=0.16$ ms. It means that at -2.5 V, the system stays predominantly in the low resistance up state. The symmetry of the RTN-like signal changes strongly with bias. At low voltages, the system stays predominantly in the high resistance down state while at high voltages, predominantly in the low resistance up state. The excess noise contribution to the total noise reaches the maximum at voltages for which $\tau_{up}=\tau_{dn}$, consistent with the properties of the classical RTN.[19]

2. Skewness

The asymmetry of a distribution is characterized by the normalized skewness $\Sigma_{i=1}^{N}(x_i-\mu)^3/N\sigma^3$, i.e., the third moment $\Sigma_{i=1}^{N}(x_i-\mu)^3/N$ normalized to the third power of the standard deviation σ^3. If the distribution is skewed positively, its mean will be larger than its median. The opposite is true for negative skewness. Gaussian noise has a zero third moment since the existence of the third moment is related to the breaking of time reversal symmetry. In this sense, measurements of the nonzero skewness are proper indications of the non-Gaussian character of the noise.

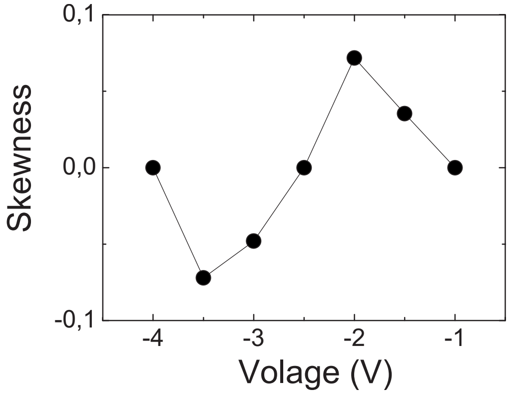

FIG. 6. Skewness of the amplitude distribution of dark current noise in a p-type QWIP as a function of bias voltage.

The bias dependence of the normalized skewness of the current noise in p-type QW is shown in Fig. 6. The change from a positive to a negative skewness around $V=-2.5$ V occurs at the same bias at which $\tau_{up}\approx\tau_{dn}$ and excess noise reaches its peak value.

In n-type QWs, the appearance of a low frequency plateau in the noise PSD has been observed at all illumination levels. However, the non-Gaussian character of the noise could have been clearly revealed only under illumination by 1000 K blackbody radiation. Moreover, in a marked difference to the noise seen in p-type QWs, no clear RTN-like wave forms appear in the current noise time traces even under 1000 K illumination. The non-Gaussian character of the photocurrent noise in n-type wells was therefore verified by measurements of the nonzero skewness shown in Fig. 7. Notice that the strength of the non-Gaussian character of the noise changes with changing bias. Similar to the case of p-type QWs, the bias dependence of the noise skewness in n-type QWs exhibits one negative and one positive maximum. The zero skewness at $V=-2.8$ V in between the peaks corresponds to the maximum of excess current noise, as it was in p-type QWs.

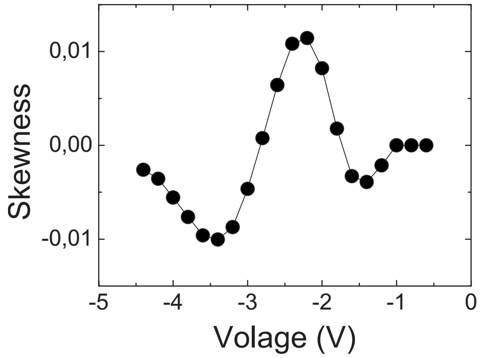

FIG. 7. Normalized skewness of an n-type QW system illuminated by 1000 K blackbody radiation as a function of the bias voltage. Note that at low and high voltages, the skewness approaches zero, as deviations from the Gaussian character of the noise become negligible.

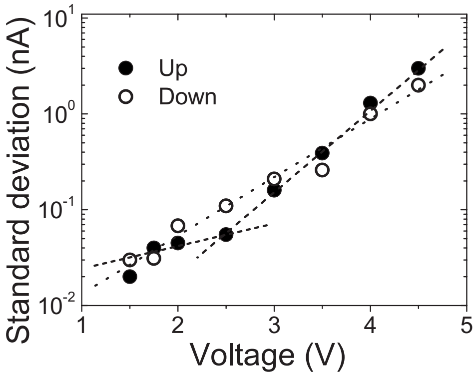

FIG. 8. Standard deviation of the current noise in a p-type QWIP at the up (full symbols) and down level (empty symbols) as a function of voltage. The dashed and dotted lines show the best fit of the data to an exponential growth in Eq. (3).

3. Standard deviation

The possibility of fitting noise amplitude distributions in p-type QWs to two overlapping Gaussian distributions enables one to easily determine the standard deviation σ of the noise at each RTN-like level. The experimentally determined σ increases exponentially with increasing bias following the law

$$\sigma = \sigma_0 \exp(\beta|V|). \tag{3}$$

The fit of the experimental data to Eq. (3) is shown in Fig. 8. For negative voltages, the fit to the down level noise yields β=1.2 V^{-1}. The standard deviation of the noise around the up level grows exponentially with β=0.6 V^{-1} for voltages below −2.5 V and with β=1.3 V^{-1} for negative voltages above −2.5 V.

According to Eq. (1), the variance of GR noise is proportional to the current. The standard deviation $\sigma=\sqrt{S_i(V)\Delta f}$ should be therefore proportional to the square root of the current. In the bias range of exponential I-V curves, the value of β is expected to be close to half of the value of α. This is true for low and high voltages. Different β values obtained at the measured voltages confirm that an additional noise mechanism, beyond the standard GR noise, contributes significantly to the dark current fluctuations in the system

Figure 9 illustrates the bias dependence of the standard deviation of current noise in the n-type QW system in dark conditions and under illumination by a blackbody radiation of 300 and 1000 K. The standard deviation of the dark current noise also increases exponentially with increasing bias. For voltages below 1.4 V and above 3.5 V, the dark current noise σ fits Eq. (3) with β=0.56 V^{-1}. Consistent with the predictions for the GR noise, this β is close to half of the value of the exponent α derived from fitting I-V characteristics to Eq. (2). However, at intermediate voltages, β =0.25 V^{-1}, which is only about one-third of the α parameter. Again, the fact that β is smaller than the expected GR value is a clear indication of a deviation from a pure GR Gaussian noise in the bias range where the excess noise appears. This proves that even in dark conditions the excess noise, different from the GR fluctuations, is present in the system even if its non-Gaussian character cannot be straightforwardly detected by the means employed in our experiments.

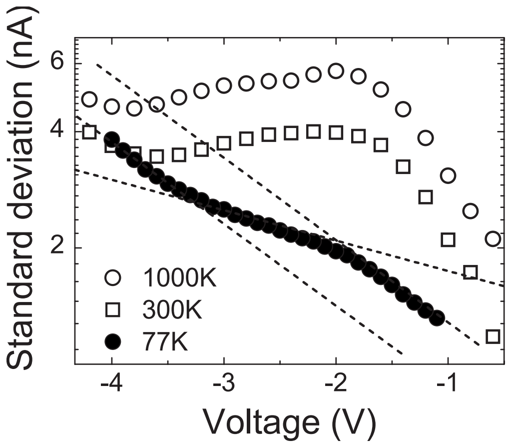

FIG. 9. Standard deviation of the current noise in n-type QWs measured at three illumination levels: 77 (dark conditions), 300, and 1000 K. The dashed lines represent the best fits of the dark current σ to Eq. (3).

Under illumination of the blackbody radiation, the standard deviation of the current noise in n-type QWs increases with increasing illumination level and deviates even stronger from the predictions of the GR model. For low negative voltages of 0.7 V$<|V|<$1.2 V, the σ under illumination fits Eq. (3) with β=1.35 V^{-1}. This β is about half of the value of α=2.77 V^{-1} derived from fitting the I-V curves measured under illumination to Eq. (2). For intermediate voltages corresponding to the bias range of the current plateau in the I-V characteristics, deviations from the expected GR noise behavior became evident, and a smaller exponent β=0.7 V^{-1} is obtained.

D. Hysteretic behavior of *I*-*V* characteristics

If the appearance of the non-Gaussian excess current noise is associated with transitions between metastable resistance states in the system, then one should expect an appearance of a hysteretic behavior in I-V curves in the bias range at which the excess noise is clearly visible. The hysteresis should be seen for sufficiently fast bias changes, which prevent the system from decaying to the equilibrium state. Indeed, such behavior was experimentally observed in n-type QWs for both positive and negative biases. Figure 10 shows I-V curves recorded under 1000 K blackbody radiation for increasing and decreasing negative biases. At intermediate voltages, within the plateau range, the I-V curves show a clear hysteretic behavior which, as expected, disappears at higher and lower voltages.

The hysteretic I-V behavior shown in Fig. 10 is consistent with a simple model of two metastable conductivity states. At high voltages, the QW system prefers to stay mainly in the up state, while at low voltages the system is mainly in the down state. When the sweep starts at high voltages and goes toward lower voltages, the system remains in nonequillibrium low resistivity, high current up state. Conversely, for the increasing voltage, the system remains in the high resistivity,

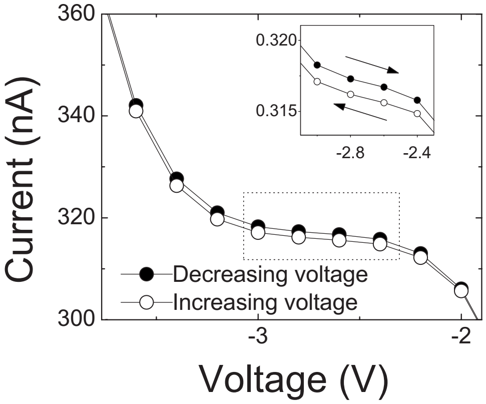

FIG. 10. Current plateau in the *I*-*V* curve of an *n*-type QW system measured for negative bias under 1000 K blackbody illumination. The hollow symbols represent data obtained with increasing bias while the filled symbols represent data recorded at decreasing bias. The inset shows a zoom of the *I*-*V* range marked with a dashed square.

low current down state. With increase of the illumination level, the hysteresis becomes more pronounced. In this case, the metastability σ and associated non-Gaussian effects become stronger.

IV. DISCUSSION

Our experiments show that excess non-Gaussian current noise appears in both *n*- and *p*-type QWs and that spectral properties of the excess noise in both types of QWs are similar. In both cases, the PSD plateau at high frequencies represents the true GR noise level, while the low frequency plateau appears due to additional excess noise processes. This conclusion is supported by the fact that the level of the high frequency PSD plateau increases with increasing bias. We have verified that at voltages at which the high frequency plateau is fully developed within our experimental frequency bandwidth, the level of the GR plateau increases exponentially with increasing bias, following $S_I(V)=S_0\exp(\gamma|V|)$, with γ being close to the value of the exponent α obtained from fitting the *I*-*V* curves to Eq. (2), exactly as expected for the GR noise.

I-*V* measurements have revealed that strong non-Gaussian noise shows out at voltages at which *I*-*V* characteristics deviate from a purely exponential behavior. Moreover, in the same voltage range, the value of the experimentally determined exponent in exponential bias dependence of standard deviation is smaller than the one expected for the GR noise mechanism in both types of QW. We conclude that the additional noise mechanism is responsible for excess noise in both *p*- and *n*-type quantum wells.

A. Metastability of electric field distribution as a source of non-Gaussian noise in quantum wells

For both types of wells, the appearance of metastable distributions of electric field seems to be a general source of excess non-Gaussian noise. At certain voltages, more than one potential distribution may possibly appear in the QW system. Such multiple potential distributions are responsible for the existence of metastable current states in the system. The nonlinear behavior due to tunneling or impact ionization induces changes in the gain. Two or more field distributions may appear for the same potential difference between the collector and emitter (the same bias), as illustrated schematically in Fig. 11(a).

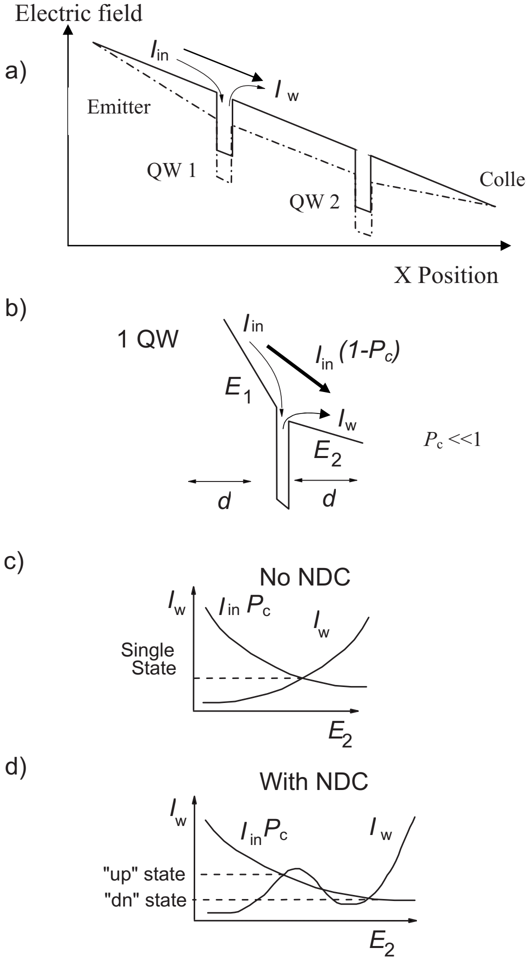

FIG. 11. (a) Example of two possible potential distributions in a QW system at the same bias voltage. Random switching between them induces non-Gaussian current noise. X labels the position, QW1 and QW2 indicate two QW barriers, and *I* is the current crossing the two-well system. (b) Physical meaning of the quantities used in the continuity equation [Eq. (4)] in a one-well system. *E* labels the electric fields of the two barriers, *I* the currents, P_c the well capture probability, and *d* the barrier thickness. (c) In the system in which current grows monotonically with increasing bias and no NDC regime, there is only a single solution to the continuity equation. (d) Negative differential conductance can lead to multiple solutions to the continuity equation in a single quantum well. *I*-*V* with the negative conductance regime is therefore a sufficient condition of appearance of excess non-Gaussian current noise.

In *n*-type wells exposed to external radiation, the additional noise can be associated with the processes of intervalley scattering resulting in two or more possible solutions to the current continuity equation

$$I_{\text{in}} = (1 - P_c)I_{\text{in}} + I_w, \tag{4}$$

where the physical nature of currents listed in the continuity equation is illustrated in Fig. 11(b) and P_c ($P_c \ll 1$) is the well capture probability. Each solution is linked with a different potential distribution in the system, corresponding to a different resistance of the system and, consequently, to a different current flow in a device. The discussed solutions are metastable, and random switching between them is the most probable mechanism of the observed non-Gaussian excess current noise.

The appearance of the negative differential conductivity (NDC) regime in the QW I-V curves is a sufficient condition for the appearance of non-Gaussian noise in a single quantum well. The continuity equation [Eq. (4)] states that the current injected to the well PI_{in} should be equal to the current coming outside of the well I_w [see Fig. 11(b)]. The total voltage drop V across a system composed of a single well and two barriers, each having the same thickness d, will be the sum of the voltage drop across the first and second barriers, respectively, $V = dE_1 + dE_2$, where E_1 and E_2 are electric fields in the relevant barrier. Usually, the current in a QW is exponentially proportional to the electric field. For a fixed bias voltage V, the field E_2 will grow with increasing I_w, while I_{in} will decrease because $E_1 = V/d - E_2$. In the absence of the NDC regime, the current I_w will increase monotonically with increasing bias voltage and the continuity equation will have only a single solution, as shown schematically in Fig. 11(c). In a marked difference, the appearance of the NDC leads to a nonmonotonic behavior of I_w (or I_{in}), which, in turn, allows for two metastable solutions to Eq. (4), as shown schematically in Fig. 11(d).

In bulk GaAs, NDC appears as a result of intervalley scattering between Γ, L, and X conduction energy bands. In QW systems, miniband tunneling[20,21] and intervalley scattering in barrier regions can significantly reduce current coming out from the wells at certain voltages. The voltage at which NDC will appear depends on the bulk properties of the material from which wells and barriers are fabricated and on the spatial configuration of QWs.[18,19] In this case, the source of current fluctuations can be a transition of the charge carriers to the lower mobility band.[22–24] Additionally, under strong illumination, the intervalley scattering in n-type QWs may generate electric field domains associated with NDC, which leads to further enhancement of the non-Gaussian component of the current noise.[25,26]

Above a certain threshold impact, ionization[27,28] could result in additional two-step-like noise. The ionization process depletes the wells, changing the voltage distribution to the dash distribution of Fig. 11(a), which is the high current metastable state. Small fluctuation in the recharging process of one well can increase the charge in that well, changing the voltage distribution to a state where the voltage is below the impact ionization threshold. In this state, the current is low and the voltage distribution follows Fig. 11(a) (solid line).

B. Difference in noise behavior between *p*- and *n*-type quantum wells

Due to the high effective mass of charge carriers, the capture probability in p-type QWs is close to unity. As a consequence, fluctuations of current coming out from a single well can dominate the current noise of the entire system. The non-Gaussianity of the noise in p-type QWs is therefore due to a dominating single elementary fluctuator associated with a single well, and RTN-like fluctuations appear in time traces of the total current noise. Difference in the rates of tunneling for light and heavy holes may cause nonlinear behavior and appearance of metastable solutions to the continuity equation at intermediate voltages. The RTN noise is known to have Lorentzian PSD, which decays as f^{-2} above the cutoff frequency, determined by the average lifetimes in both RTN states $f_c = 1/\tau_{up} + 1/\tau_{dn}$. This type of spectral behavior can be seen in PSD of the current noise of p-type device at $V = 2.5$ V in Fig. 1. Note that in the scenario of RTN-like jumps between high and low metastable current states, the change of the electric field distribution is almost instantaneous, while the current responds within the recharging RC time constant, as indeed seen in the experiments.

N-type QWs have significantly higher gain than the p-type well, and all QWs of the device contribute to the current noise. Possible non-Gaussian current fluctuations of individual wells are incoherently superimposed. As a result, measurable manifestations of non-Gaussian noise in n-type QWs can be seen only in nonzero skewness of the noise amplitude distributions recorded under illumination (see Fig. 7). Moreover, the metastable potential distributions in n-type QWs can be associated with the NDC regime and strong nonlinearity of I-V curves, which are stronger under illumination.

Skewness, or the normalized third moment, exhibits a positive peak at -2.2 V and a negative one at -3.4 V, and a secondary maximum at -1.8 V. The skewness reaches zero at $V = -2.8$ V, but the kurtosis (fourth moment) of the distribution at this bias is markedly different from the Gaussian value. The zero skewness voltage coincides with the voltage of the maxima in dynamic resistivity peak and normalized PSD. Voltage shift at high illumination levels can be attributed to changes in the electric field distribution induced by the illumination. With increasing illumination temperature, the electric field in the barriers close to the emitter becomes higher, while that in the barriers closer to the collector decreases.[25] Thus, an extra voltage is needed for the wells closer to the collector to contribute to the fluctuations.

Modifications of I-V curves induced by external illumination, illustrated previously in Fig. 4, can be better seen in the plots of voltage dependence of the differential resistance $\rho = dV/dI$ shown in Fig. 12(a). The nonmonotonic behavior of ρ seen at all illumination levels becomes significantly enhanced with increasing illumination level. Moreover, voltages at which the maxima of differential resistance appear, change with changing illumination level. At 77 K, the maximum is located at -2.2 V, while for 300 and 1000 K illumination, the peak shifts up to -2.8 V.

Figure 12(b) shows the voltage dependence of the level of the low frequency plateau in current noise PSD normalized to the square of the dc current, $S_i = S_I/I^2$. The maximum of the noise coincides here with the center of the current plateau in I-V curves, clearly indicating that additional noise sources are active in the intermediate bias range. Bias dependence of the differential resistance provides yet another connection

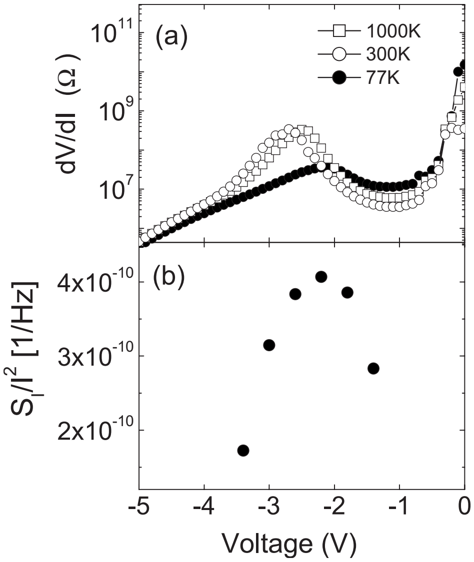

FIG. 12. (a) Differential resistance of n-type QWs illuminated by 77, 300, and 1000 K radiation. (b) Bias dependence of the normalized PSD, $S_i = S_I/I^2$ at 100 Hz for 77 K background radiation.

between the excess noise and the NDC regime. The voltage at which the normalized PSD reaches the maximum coincides with the voltage at which differential resistivity in n-type QW system goes through a maximum.

Current plateaus and the differential resistivity maxima, which can be related to intervalley scattering,[20] are more pronounced at negative bias voltages. The asymmetry between positive and negative voltages may be attributed to differences between barriers of the emitter and collector or to asymmetric doping.[21]

The gain in n-type QWs calculated using Eq. (1) for dark conditions and for the 300 K illumination case is plotted in Fig. 13 as a function of bias voltage. The character of the dependence is very similar to that of Fig. 12. One can therefore relate low frequency noise to the nonlinear behavior of the gain, which is consistent with the intervalley scattering scenario.[20,21] Under illumination conditions, the shape of the bias dependence of the gain in Fig. 13 resembles the shape of the bias dependence of the standard deviation in Fig. 9. This additionally supports the conclusion that intervalley scattering is responsible for non-Gaussian noise in n-type QWs.

V. CONCLUSIONS

We have observed non-Gaussian noise components in both n-type and p-type quantum wells. The non-Gaussian character of the noise is significantly more pronounced in p-type wells where clear random telegraphlike fluctuations appear in time domain records of current fluctuations. In n-type wells, non-Gaussianity of the noise has been demonstrated by measurements of the nonzero third moment. We attribute different degrees of non-Gaussian character of the noise to different capture probabilities in both types of wells. The noise can be related to a nonlinear behavior of the gain, resulting in metastable potential distributions. In the p type, the nonlinearity can be attributed to the difference in tunneling rates for light and heavy holes. For n-type wells, the intervalley scattering seems to be the dominant reason for the appearance of the nonlinear gain. In both cases, additional non-Gaussian noise can originate from impact ionization. Our five-well sample creates several possible voltage distributions. In that way, in order to differentiate between the suggested mechanisms, experiments on a one-well sample should be done.

The appearance of non-Gaussian noise is attributed to two solutions of the continuity equation in the NDC regime, allowing for the existence of two metastable spatial voltage distributions. Two distinct spatial voltage distributions under a constant external bias voltage correspond to two possible states of the system: a high resistivity state with low current and a low resistivity state with high current. Each state is characterized by its specific bias dependent average lifetime. The finite time of transition between the metastable states, which is not negligible with respect to the average lifetimes, is determined by the charging time constant by the capacitance and resistance of the QW system.

For practical purposes, at the nonexponential regime of the current, where we have negative differential gain, excess noise could appear. In those regimes, the noise will reduce the signal-to-noise ratio, reducing the device function ability. A change in the operating voltage moving out of the metastable area will improve the signal-to-noise ratio.

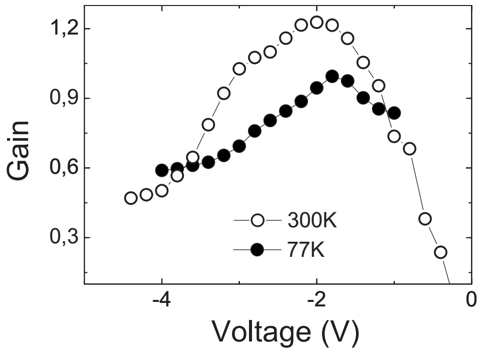

FIG. 13. Gain of n-type QWs in dark conditions and under illumination by 300 K background radiation.

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