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Light-induced stochastic resonance in a nanoscale resonant-tunneling diode

F. Hartmann,[1,a)] L. Gammaitoni,[2] S. Höfling,[1] A. Forchel,[1] and L. Worschech[1]
[1]*Technische Physik, Physikalisches Institut, Wilhelm Conrad Röntgen Research Center for Complex Material Systems, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*
[2]*NiPS Laboratory, Dipartimento di Fisica, Universita di Perugia, I-06123 Perugia, Italy and Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy*

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Resonant tunneling diodes (RTDs) have been often invoked as a primary nanoelectronic device candidate for cellular neural network physical implementation and for mimicking biological neuronlike behaviors. In this letter we report on the light-induced behavior of trench-etched RTDs capable of undergoing complex stochastic dynamics where electronic noise and light can cooperate for reproducing the stochastic resonance phenomenon previously observed in real biological neurons. The experimental measurements presented here add a missing piece to the quest for the optimal mimicking of bio-neural simulation by improving the functionality and thus the potential role of nanoscale RTDs. © *2011 American Institute of Physics*. [doi:10.1063/1.3600329]

Resonant tunneling diodes (RTDs) have been demonstrated to show a number of interesting functional properties for the implementation of cellular neural network (CNN) that make them a strong candidate in the search of an ideal device to realize CNN. RTDs have shown superior performance in terms of complexity, functionality, or processing speed compared to standard cells.[1] Moreover, RTDs are often invoked as a useful conceptual device for the simulation of biological neurons mostly in the form of threshold logic gates[2] derived from the pioneering work of McCulloch and Pitts[3] on the model of an artificial neuron.

In this letter we show that similar to what has been observed for a biological neuron, RTDs with an open contact layout can show complex light-induced behavior, including the phenomenon of stochastic resonance (SR)[4] that has become the hallmark of stochastic nonlinear dynamics observed in a number of different physical systems. SR has gained large popularity due to its observation in biological sensory neuron experiments[5] and it has been included in the phenomenology of neuron models.[6] On the other hand, noise and stochastic nonlinear dynamics are considered nowadays a fundamental ingredient in the study of neuron dynamics[7] and noise has also shown to play a significant role in RTD functioning.[8] In the following, we present detailed noise-activated measurements in RTDs at room temperature. If biased in the bistable regime, these RTDs show pronounced noise-activated switching, which can be tuned sensitively by the applied noise. It is demonstrated that SR can be tuned by exposing the RTD to light. In particular, it is found that SR can be enhanced by increasing the light power.

In order to study the RTD light-induced behavior, we fabricated trench-etched RTDs. In Fig. 1(a) a sketch of the layer sequence of the molecular-beam grown RTDs, electron microscopy images, and the electronic circuit diagram are shown. The RTDs are based on a GaAs system. The central undoped double barrier structure consists of a 4 nm thick GaAs quantum well embedded in 3 nm thick $Al_{0.6}Ga_{0.4}As$ barriers. Highly doped GaAs drain and source layers serve as contacts of the structure. Dry chemical etching was applied to define RTD mesas with diameters ranging from d=2 μm down to 600 nm. Additionally, a central trench with a width of 150 nm was etched into the structure. At the stem, the bias voltage was applied with the top contact serving as ground. The bias voltage consists of a static dc voltage V_{dc} superimposed by a periodic voltage V_{ac} and a stochastic voltage signal V_{noise} generated by a noise source. V_{noise} is uncorrelated and Gaussian-distributed with a cutoff frequency of 20 MHz. Due to the etched central trench,

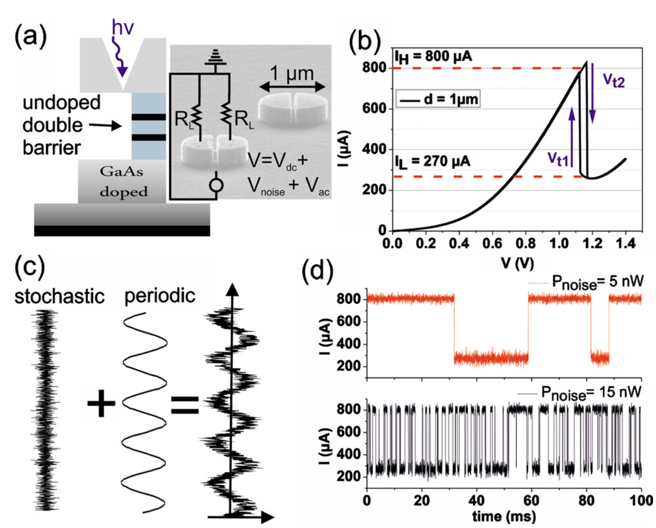

FIG. 1. (Color online) (a) Layer sequence of the trench-etched RTD. Also shown are electron microscopy images of RTD mesas together with the electronic circuit diagram. The RTD is biased with a static dc voltage V_{dc} superimposed by a stochastic V_{noise} and periodic V_{ac} component and the output is measured as voltage drop across R_L=100 Ω. (b) I(V) characteristic of an RTD mesa with diameter d=1 μm measured at room temperature. The RTD shows bistable characteristics with a hysteresis width of about 32 mV, threshold switching voltages V_{t1} and V_{t2}, and two stable outputs with I_H=800 μA (high) and I_L=270 μA (low). (c) The RTD is biased with V_{dc} symmetric between V_{t1} and V_{t2} and additionally a periodic V_{ac} and a stochastic force V_{noise} is applied. (d) Time trace signals for noise powers P_{noise}=5 and 15 nW without an external periodic modulation. The bistable character of the structure is apparent and the switching events are given by the inverse of the Kramer's rate r_k.

[a)]Electronic mail: fhartmann@physik.uni-wuerzburg.de.

electron-holes pairs can be efficiently excited in the RTD by laser-light focused at the central trench with a photon energy larger than the band gap of GaAs. In the electric field of the biased RTD, the electron-hole pairs become separated, which in turn modulates the internal electric field of the RTD. As a consequence, the RTD I-V curve and in particular the threshold voltages at the bistable transitions are changed due to light exposure of RTDs.[9]

In Fig. 1(b) a current-voltage characteristic of an RTD with a diameter $d=1$ μm conducted at room temperature is shown. The RTD shows bistable transitions in the up and down sweep of the bias voltage with two stable outputs, a resonance (*high*) and valley (*low*) state with output currents $I_H=800$ and $I_L=270$ μA, respectively. The hysteresis width is around 32 mV with switching threshold voltages V_{t1} from the low to the high state and V_{t2}, vice versa. Within the bias range $V_{t1}<V<V_{t2}$ the bistable character of the RTD is apparent. In the following, the RTD was biased by the static component symmetrically between V_{t1} and V_{t2}. Adding now a periodic signal superimposed by noise [Fig. 1(c)] pronounced noise activated switching occurs. We performed following experiments. Either a periodic sine-wave ac voltage signal with amplitude V_{ac} and frequency $f=500$ Hz or a mechanically chopped periodic light modulation with the same frequency and light energy of $E_{light}=2.76$ eV served as periodical input.

The laser was focused on the central trench of the RTD, which allows efficient light absorption close to the double barrier structure. Without the periodic modulation, due to the stochastic forcing, noise-activated switching of the RTD between its two stable outputs can be found with a characteristic time scale given by the inverse of the famous Kramer's rate r_k.[10] In Fig. 1(d) signal trains for noise powers $P_{noise}=5$ and 15 nW are shown. Here, no periodic forcing was applied. In the SR scenario, such noise-activated time scale can be synchronized at an optimum level with a weak periodic signal. The SR phenomenon was originally introduced in 1981 to explain the periodicity in the earth's climate change,[11] and manifests itself in a synchronization of the noise with a weak periodic signal. Since its introduction SR has become quite popular and it has been found in many different systems.[12] In recent years, a specific attention to SR has been devoted in micro and nanoelectronics[13] and also in the biophysical realm with reference to sensory neurons[14] where it has been observed in the mechanoreceptors of different animals, such as crickets[15] or crayfishes.[5]

In Fig. 2(a) different signal trains of the RTD output for noise powers below ($P_{noise}=2$ nW; top), in ($P_{noise}=17$ nW; middle), and above ($P_{noise}=112$ nW; bottom) the optimum SR noise power are shown for a weak ac sine-wave periodic modulation with an amplitude $V_{ac}=5.3$ mV. For $P_{noise}=2$ nW, the system switches randomly between its *high* and *low* state with a small number of switching events. At the optimum SR noise power $P_{noise}=17$ nW, the output of the RTD follows almost perfectly the weak periodic forcing with frequency $f=500$ Hz. This optimum synchronization process vanishes as the noise power is increased. In order to show the SR phenomenon in our RTD device, we computed fast Fourier transforms for the curves conducted for different noise powers $P_{noise}=2, 17$ and 112 nW [in Fig. 2(b), top to bottom curves, respectively]. For a small noise power, $P_{noise}=2$ nW (top), no spectral component at $f=500$ Hz is apparent. In this condition the switching events are very rare, i.e., the periodic component of the input signal is not able to activate periodic dynamics of the switch between the two stable states. The RTD dynamics are dominated here by the so-called "intrawell motion" and the system output is confined around the potential minima. On the contrary, for large noise power, above the optimum SR condition [$P=112$ nW, bottom in Fig. 2(b)] the switching events between the two stable states are mainly random, dominated by the noisy component of the input signal. In this case the amplitude of the spectral component with $\langle V(f=500 \text{ Hz})\rangle=-44$ dbV is still observable, but less pronounced compared to the optimum SR condition. Finally, it exists an optimal noise power condition [$P_{noise}=17$ nW, middle in Fig. 2(b)] where the spectral component exhibits a maximum of -37 dbV. This is the SR condition and the stochastic and the periodic forcing are matched at an optimum level.

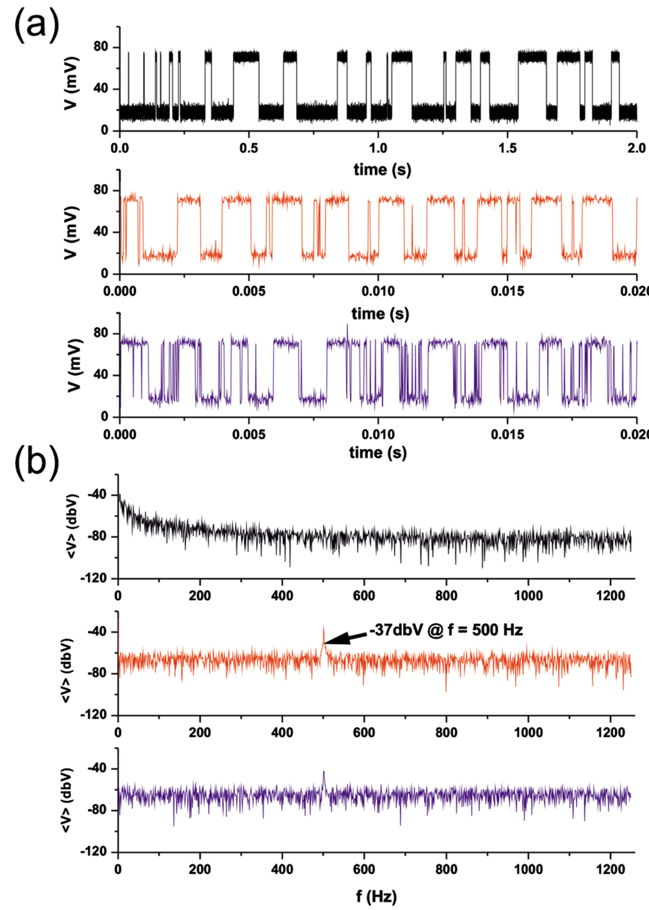

FIG. 2. (Color online) (a) Time trace signals for noise powers $P_{noise}=2$, 17, and 112 nW (top to bottom) for a weak ac modulation with amplitude $V_{ac}=5.3$ mV. For $P_{noise}=2$ nW (top) the output is predominantly controlled by the noise floor. At the SR noise power $P_{noise}=17$ nW (middle), an optimum synchronization can be found which vanishes as the noise power increases up to 112 nW (bottom). (b) Fourier-transforms of the time trace signals shown in (a). For a small noise power, $P_{noise}=2$ nW (top), no spectral component at the periodic signal can be observed. At $P_{noise}=17$ nW (middle), the spectral component reaches a maximum with $\langle V(f=500 \text{ Hz})\rangle=-37$ dbV, which decreases for an increased noise power (bottom curve corresponds to $P_{noise}=112$ nW).

This is quantitatively shown in Fig. 3(a) where the spectral amplitude $\langle V\rangle$ of the periodic component at $f=500$ Hz as a function of the noise power for a weak ac modulation with amplitudes V_{ac} from 2.2 to 7.5 mV is shown. With increasing noise power, the spectral components first increase, pass through a maximum at $P_{noise}=17$ nW and de-

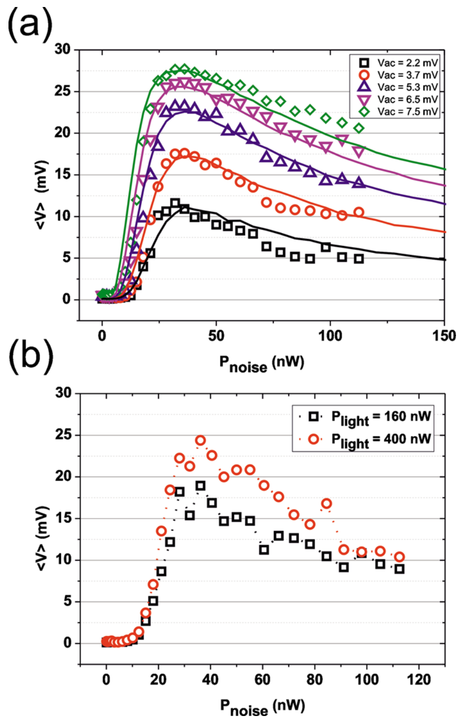

FIG. 3. (Color online) Amplitude $\langle V \rangle$ of the periodic component under ac modulation in (a) for different amplitudes V_{ac} from 2.2 to 7.5 mV and for external light modulation in (b) with light powers $P_{light}=160$ and 400 nW as function of the applied noise power P_{noise}. (a) The amplitude of the spectral component (scatter: measurement; line: simulation) first increases, passes through a maximum at $P_{noise}=17$ nW and finally decreases again. For each amplitude V_{ac}, $\langle V \rangle$ is enhanced for noise powers at around 17 nW, thus SR is achieved. (b) $\langle V \rangle$ under a weak external periodic light modulation with light powers $P_{light}=160$ and 400 nW shows a similar behavior with the data presented in (a).

crease again. The optimum noise power is independent of the amplitude of the periodic forcing, but dependent only on the frequency of the periodic forcing. Also shown are numerical simulations (solid lines) based on an ideal two-level Schmitt-trigger model with all simulation parameters adapted from the experiment, e.g., the barrier height was set to 16 mV as the hysteresis width of the device was 32 mV.[8,16] The uncorrelated noise is Gaussian distributed with zero mean and standard deviation σ_{noise}. The simulation output agrees very well with the experiment.

Up to this point, one can see that a weak voltage signal with periodic forcing can be synchronized with the stochastic time scale of the system. It is demonstrated in the following, that this behavior can also be achieved with a weak periodic illumination of the RTD as well. This occurrence is of certain interest in the quest for an electronic device capable of mimicking biological neurons. As a matter of fact, the light sensitivity is a well known feature of systems of biological neurons and in recent years the interplay of noise and light has attracted researchers' attention.[17]

In Fig. 3(b) the spectral amplitude $\langle V \rangle$ of the RTD periodic component as a function of the noise power for a weak periodic illumination with light powers $P_{light}=160$ and 400 nW is presented. Here we chopped the light mechanically with the same frequency f=500 Hz as the periodic signal employed in Fig. 3(a). For this measurement V_{ac} was zero. Although no periodic electric signal was applied in this case, the SR phenomenon is well apparent and with features very similar to those observed in Fig. 3(a).

In summary, light-modulated stochastic dynamics of trench-etched RTDs, as potential candidate for artificial neuronlike devices, were studied at room temperature. SR was found for noise powers of $P_{noise}=17$ nW at a periodic forcing frequency of f=500 Hz. SR is demonstrated either for a weak ac bias voltage modulation with a minimum amplitude of $V_{ac}=2.2$ mV or by a weak periodic illumination of the RTD. A maximum in the spectral amplitude of the system was observed and was associated with an optimum synchronization, i.e., SR was fully achieved. This observation adds to the features that make the RTD an optimal choice for the implementation of CNN and a potential candidate for the mimicking of biological neurons.

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