Noise and terahertz rectification linked by geometry in planar asymmetric nanodiodes

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In this work, by means of Monte Carlo simulations, we evidence the presence of a terahertz resonant peak in the ac to dc rectification of planar asymmetric nanodiodes which, remarkably, is linked to a noise mechanism, collective charge fluctuations in the space-charge region around the active channel of the device. The current noise spectral density of the diodes is compared with the frequency-dependent ac to dc rectification with the aim of identifying the signature of the phenomenon in both quantities. The frequency and magnitude of the resonance can be tuned by modifying the diode geometry. Results are interpreted in terms of an equivalent circuit model.
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The development of compact, low-cost semiconductor devices operating at terahertz frequencies is one of the challenges of nanoelectronics in a medium term future. Great efforts are being made to build compact terahertz systems operating at room temperature, with the lowest level of noise. Several physical mechanisms have been explored to this end. Among them, collective phenomena seem to be a promising possibility. For example, plasma oscillations in the two-dimensional (2D) electron gas of nanometer field effect transistors have been explored in the last years in order to develop terahertz emitters and detectors.[1–3] Transit time resonance assisted by optical phonon emission in wide band-gap semiconductors and related plasma instabilities are another possibility, predicted by theory and confirmed by simulations.[4,5] In this work, we explore a high frequency collective phenomenon present in an asymmetric nanodiode, the so called self-switching diode (SSD).[6] By virtue of its geometry, a peak in the current noise spectrum is coupled to the dc response of the device, thus originating a terahertz resonance in the rectification of ac signals.

SSDs are planar diodes fabricated with just one lithographic step by simply etching L-shaped insulating grooves onto a semiconductor layer, thus defining a narrow channel with broken symmetry, as shown in the inset of Fig. 1. This particular geometry originates a strongly nonlinear rectifying *I-V* characteristic, consequence of the opening/closing of the channel due to the field effect of the surrounding regions.[7] The planar architecture allows obtaining a parasitic capacitance between contacts substantially lower than in conventional vertical devices of the same size. It also permits fabricating arrays of many SSDs in parallel, thus overcoming the important problem of the high input resistance of discrete devices. The use of fast III–V materials (InGaAs channels) provides an excellent frequency performance, experimentally confirmed up to 110 GHz at 300 K (Ref. 8) and 1–2 THz at low temperature.[9]

In previous works, the Monte Carlo (MC) analysis of the current noise spectra of submicron SSDs evidenced the presence of a peak around 1 THz.[10,11] The exact frequency of such a peak was found to depend mainly on the width of the vertical trenches. On the other hand, the analysis of the dynamic response of SSDs showed that the mean current flowing through the device when applying an ac bias between terminals exhibits a resonance at frequencies in the range of

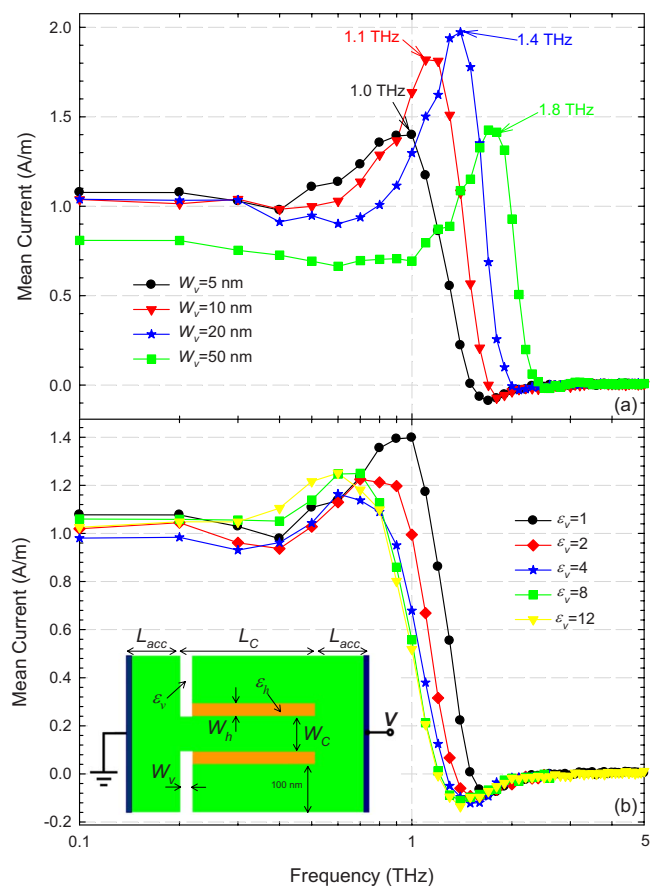

FIG. 1. (Color online) Mean current vs frequency of the applied ac voltage (amplitude of 0.25 V) in SSDs with the topology of the inset for: (a) different values of W_v and $\varepsilon_v=1$ and (b) different values of ε_v and $W_v=5$ nm. $L_C=250$ nm, $W_C=50$ nm, $W_h=5$ nm, $\varepsilon_h=1$, and $L_{acc}=175$ nm.

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1–2 THz. The exact position of the resonance was dependent on the permittivity of the vertical trenches.[12] The aim of this work is to show that both resonant effects, found in the noise and ac to dc rectification, are linked, being the same collective phenomenon which originates the presence of the peak in both quantities. The key point for the phenomenon, as demonstrated in Ref. 12, is the presence of collective charge fluctuations near the vertical trenches whose origin is not completely clear. While in Ref. 12 localized surface plasma (LSP) oscillations were claimed to be responsible for the fluctuations, in Ref. 10 they were attributed to returning carrier effects. Independent of the physical origin, in this device the processes increasing current noise, with a characteristic frequency that can be controlled by the geometry, provides an enhancement of its response to ac signals. This fact allows the thinking of applications of SSDs as detectors of terahertz signals with a certain degree of frequency selectivity.

For the analysis we make use of a MC simulator successfully employed in previous works for the study of SSDs[7,10] and different types of InGaAs based nanodevices.[13] It consists of a semiclassical MC simulator self-consistently coupled with a 2D Poisson solver. The model includes the presence of surface charges at the semiconductor-dielectric boundaries, key for the behavior of SSDs. Further details about the model can be found in Ref. 13. All calculations are made at 300 K in SSDs with InGaAs channels. The topology of the SSDs under analysis, the same used in Ref. 10, is shown in the inset of Fig. 1(b). We investigated diodes with channel length $L_C=250$ nm, channel width $W_C=50$ nm, width of the horizontal trenches $W_h=5$ nm, relative permittivity of the horizontal trenches $\varepsilon_h=1$, and length of the accesses $L_{acc}=175$ nm. In our study, different values of the width, of the vertical trenches W_v, and of their relative permittivity ε_v have been considered.

Initially we analyzed the dynamic behavior of SSDs in terms of their ac to dc rectification. Harmonic voltage signals $V=V_0 \sin(2\pi ft)$ of increasing frequency f are applied between the contacts and the dc output current is evaluated. Figure 1(a) shows the results for SSDs with different widths of the vertical trenches W_v and $\varepsilon_v=1$ (with $V_0=0.25$ V). After a flat region at the lower frequencies, the rectified current exhibits a pronounced peak, just before the decay in the response. The frequency of the peak f_p is shifted to higher values for wider vertical trenches. The peak is also sensitive to the permittivity of the vertical trenches ε_v, as observed in Fig. 1(b), corresponding to SSDs where $W_v=5$ nm and ε_v takes different values. In this case, f_p shifts to lower frequencies as ε_v is increased, saturating for $\varepsilon_v>4$ (to be explained later). It is worth noting here that the position of the peak has been found to be insensitive to the properties of the horizontal trench W_h and ε_h (results not reported here).

The observed dependence of f_p on W_v and ε_v suggests a strong influence of the capacitor associated with the vertical trenches $C_v=\varepsilon_v/W_v$ on the phenomenon originating the resonance; that is why the effect of ε_v and W_v on f_p is totally opposite. As demonstrated in Ref. 12, the regions of the diode having the strongest influence on the modulation of the channel conductance, which lead to the observed resonant dc rectified current, are those surrounding the channel close to the vertical trenches. Indeed, the barrier that controls the flow of carriers through the channel under forward bias conditions is located just at its left entrance. The amplitude of such a barrier is strongly modulated by the charge variations within the outside surrounding regions (close to the vertical trenches), which are obviously regulated by C_v.

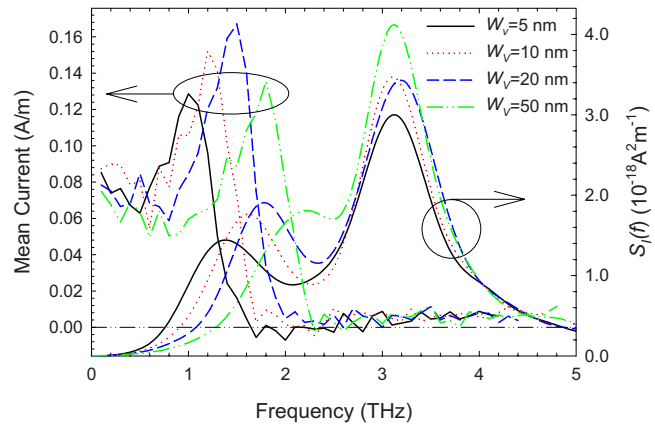

FIG. 2. (Color online) Comparison of the current noise spectra (right axis) calculated at equilibrium (results already published in Ref. 10) and the dc rectified current (left axis) when the amplitude of the ac excitation is 0.15 V for diodes with different W_v and $\varepsilon_v=1$.

The MC analysis of the current noise spectral density in SSDs performed in Ref. 10 evidenced the presence of a peak with a dependence on W_v analogous to that observed in the case of the rectifying response. To identify the similarities, in Fig. 2, we compare the frequency dependence of the current noise spectral density $S_I(f)$ (calculated at equilibrium) with that of the dc rectified current in SSDs with different W_v. Here the amplitude of the ac excitation is $V_0=0.15$ V, providing a sharper peak slightly shifted to higher frequencies (as compared to the results shown in Fig. 1, where $V_0=0.25$ V). If we focus on the noise spectra, two peaks are observed. The one at higher frequency, at around 3 THz independently of W_v, is due to three-dimensional (3D) plasma oscillations.[10] The peak at lower frequency (in the range of 1–2 THz) exhibits a dependence on W_v quite similar to that observed in the dc rectified current. This indicates that, quite probably, we are observing the same microscopic phenomenon displayed in different macroscopic quantities.

Based on MC simulations, earlier works[10,11] interpreted the origin of the peak in the noise in terms of the dynamics of the carriers reflected back at both sidewalls of the vertical trenches, so-called returning carriers.[14] Charge fluctuations would then be caused by the deceleration/acceleration of electrons at the potential barrier created by surface charge at the interfaces of the vertical trenches. In the study of the resonance in rectification performed in Ref. 12, charge fluctuations were provided an alternative explanation, the presence of LSP oscillations. Both interpretations are compatible, since, as explained in Ref. 14, the dynamics of returning carries is closely connected to plasma oscillations. In fact, the characteristic time of a returning electron is $\tau_r=\pi/\omega_p$, with ω_p the angular plasma frequency, so that returning carrier noise is the result of plasma oscillations within the depletion region adjacent to a barrier.

Independent of its origin, what is remarkable is that a resonance in the collective charge fluctuations in the space-charge region around the vertical trenches simultaneously couples to the current noise and the dc response to ac excitations. In the case of the noise the coupling to the terminals occurs through the capacitance of the vertical trenches C_v.

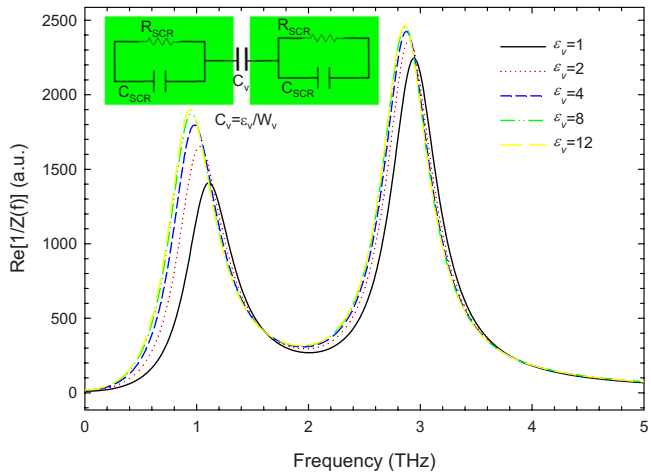

FIG. 3. (Color online) Real part of the admittance for diodes with different ε_v.

For the rectification, an additional coupling through the horizontal trenches takes place.

It must be remembered that the spectral density of current fluctuations at equilibrium is proportional to the small signal admittance of the device,[15] whereas the dc response current is caused by the diode rectification and corresponds to large signal operating conditions. Moreover, the rectified current is frequency shifted by the horizontal capacitor, while the noise is only influenced by the vertical one (with no need of the presence of a conducting channel). All these facts explain why the frequency of the peak does not coincide exactly in both quantities and why similarities are more pronounced the lower the amplitude of the ac excitation (situation closer to small signal conditions). Concerning the 3D plasma peak around 3 THz observed in the noise spectra, it is mainly originated by charge fluctuations in the access regions of the diode which do not couple to the conductance of the channel. That is the reason why it appears in the noise spectra and not in the dc rectified current.

In order to confirm that the capacitance associated with the vertical trenches C_v is essential in the resonance, two diodes with different values of W_v and ε_v, but adjusted to provide the same C_v, have been simulated. The obtained current noise spectra are practically identical, thus certifying our interpretation.

Finally, to explain the saturation in the shift of the low frequency peak observed for $\varepsilon_v > 4$ in Fig. 1(b), we use the equivalent circuit proposed in Ref. 10 to calculate the noise spectra in terms of the frequency dependence of the diode admittance $Y(f)$; $S_I(f) = 4K_BT\,\mathrm{Re}[Y(f)]$ at equilibrium. As a novelty, a capacitor and a resistance, R_{SCR} and C_{SCR}, respectively, are used to model the space charge region at both sides of the trenches, placed in series with C_v as drawn in the inset of Fig. 3. C_{SCR} is the capacitance of the depletion region originated by the surface charges present at the vertical trenches. As a consequence of the series combination of C_v and C_{SCR}, the equivalent capacitance is fixed by the lowest one. Thus, when ε_v is increased and C_v becomes much higher than C_{SCR} (what happens for $\varepsilon_v > 4$), the equivalent capacitance is practically C_{SCR}. Above that limit the position of the low frequency peak does not change, as observed in the spectra predicted by the equivalent circuit shown in Fig. 3.

In conclusion, by means of MC simulations we evidenced the common origin of the resonant peak previously found both in the current noise spectra and ac to dc rectification of SSDs. The frequency of such a resonance can be tuned in the terahertz range by means of the geometry of the diodes, modifying the width or the dielectric material of the vertical trenches. This can be quite useful for detection applications. Despite the low amplitude and quality factor of the peak observed in the reported results, we checked that they can be improved by: (i) using semiconductors with higher mobility (such as InAs or InSb), (ii) decreasing the operation temperature, and (iii) reducing the channel length. In all cases, the more ballistic character of transport not only enhances the response but also shifts the resonant peak to higher frequencies, thus also improving the frequency tuning range. This will be the object of future works.

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