Gunn oscillations in a self-switching nanodiode

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The feasibility of Gunn oscillations in a planar nanoscale unipolar diode or a self-switching device (SSD) is analyzed using Monte Carlo simulations. The asymmetric nanochannel that the SSD is based on is shown to induce charge domains much more receptively when compared to a reference symmetric nanochannel. The oscillation frequency reaches 130 GHz. Potential applications are discussed in terms of the ease of heat dissipation and generation of oscillations at different frequencies on a single chip, in contrast to a conventional vertical-structure Gunn diode. © 2008 American Institute of Physics. [DOI: 10.1063/1.3042268]

The terahertz (1 THz=1000 GHz) region of the electromagnetic spectrum is relatively unexplored when compared with the well-developed technologies of infrared light and microwaves in the adjacent frequency bands. Utilizing terahertz waves could enable very broad applications ranging from nondestructive imaging and spectroscopy of biological materials, remote detection of hidden objects and explosives, to manipulations of quantum states in semiconductors.1 Development of semiconductor terahertz electronic devices is certainly also paramount and timely to future generation of large-volume information processing and high-performance computations. However, terahertz technology is so far largely hampered by the lack of solid-state, room-temperature detectors and sources.2 Although quantum-cascade lasers have been demonstrated to work at a few terahertz,3 it remains extremely challenging to achieve room-temperature operations.

Nanostructure devices based on two-dimensional electron gases (2DEGs) in semiconductor heterostructures have been demonstrated for operations at tens of gigahertz or above.4–7 In particular, self-switching diodes (SSDs) have been shown to have a zero threshold voltage and be able to rectify microwave signals up to 110 GHz at room temperature. Theoretical work has predicted operations at terahertz frequencies.8–13 The high speeds are largely due to the planar architectures of these devices, i.e., the electrodes are connected side by side to the active semiconductor layer rather than placed on top of each other, as in conventional multilayered vertical-structured devices. As such, very low parasitic capacitances are attainable. Microwave detectors and frequency multipliers can be achieved by straightforward integration of arrays of SSDs in parallel in order to reduce overall impedance, without a need for interconnects between the devices.14 Very recently, microwave detection up to 2.5 THz was demonstrated using an SSD array at a temperature of 150 K.15 Apart from terahertz detectors, development of active devices, particularly emitters, is also timely. Gunn-effect oscillator is often used as a microwave emitter.16 If an electric field in a semiconductor is beyond a threshold to induce a negative differential velocity, a charge carrier domain forms due to the slow down of the carriers. The domain moves at a lower velocity than the carriers behind the domain. The domain grows in size as it moves because carriers from behind catch up and join the domain. Once the domain reaches the device terminal, another domain will be formed and the above process repeats. The frequency of the current oscillation was typically determined by the domain velocity and the length of device active region.16 In this work, using a 2D ensemble Monte Carlo (EMC) method, we show that Gunn oscillations can occur in SSDs under appropriate conditions, allowing SSDs to operate also as an active device to generate rf power.

Figure 1(a) schematically shows the top view of the SSD. The device is based on an In0.53Ga0.47As/In0.53Al0.47As heterostructure, where a 2DEG is formed at the heterointerface with a carrier concentration of $1.0 \times 10^{12}$ cm$^{-2}$. The two L-shaped insulating trenches are etched through the 2DEG layer, which ensures that electrons have to pass the narrow channel between the two trenches in order to conduct a current between the left and right terminals. When a negative voltage is applied to the right terminal, the induced negative charges around the trenches deplete the channel, impeding the current flow, thus switching the device off. However, when a positive voltage is applied to the right terminal, the induced positive charges around the trenches attract electrons into the channel for the current to flow easily. This leads to diodelike characteristics, as demonstrated experimentally.14 Although the current-voltage characteristic of a SSD is similar to that of a $p-n$ junction or Schottky barrier diode, it is based on neither a doping junction nor a tunneling barrier, i.e., no built-in electric field along the current direction. As such, the threshold voltage could be made to be zero, ideal for microwave applications.

A semiclassical EMC method self-consistently coupled with the Poisson equation is used here.17 As in earlier work,10–12 some theoretical assumptions are made in order to enhance the efficiency of the EMC simulations. First, 2D EMC simulations are performed only on the active In0.53Ga0.47As layer since it is the 2DEG layer that largely determines the electronic properties of the device. Second, to
account for the fixed positive charges of the doping layer, a virtual net background doping \( N_0 = 1.0 \times 10^{17} \text{ cm}^{-3} \) (without ionized impurity scattering) is assigned to the In$_{0.53}$Ga$_{0.47}$As layer. In order to model the influence of surface states at semiconductor-air interface, a uniform negative charge density \( N_S = 0.2 \times 10^{12} \text{ cm}^{-2} \) is also added at the edge of the insulating trenches during the simulations. The SSD was designed with a channel width of \( W_c = 60 \text{ nm} \) and a horizontal trench width of \( W_{ht} = 60 \text{ nm} \). Other geometric parameters are defined in Fig. 1(a). All simulations are carried out at room temperature with the left terminal grounded.

The solid line in Fig. 2 shows the channel current as a function of time. At time zero, the applied dc voltage to the right terminal changes from 2.5 to 3.0 V, and then maintains that value for 80 ps. A sharp rise and fall of the current are shown after the abrupt change of the applied voltage, which is anticipated as a result of the charging of parasitic capacitances in the device. Subsequently, a sustained current oscillation of a peak-to-peak value of about 10 \( \mu \text{A} \) is observed, providing the bias voltage remains at 3.0 V. The oscillation period is about 7.5 ps, corresponding to a frequency of about 130 GHz.

A few observations indicate that the phenomenon may be related to the Gunn oscillation. Below 3.0 V, no sustained oscillations are observed. This corresponds to a threshold electric field in the same order of magnitude as in conventional Gunn diodes made of a similar material. The oscillation period corresponds well to the value given by the length of the nanochannel divided by the carrier saturation velocity obtained from previous work.\(^{10}\) In order to unambiguously verify if the oscillation is related to the Gunn effect, the evolution of charge domains as a function of the time and position in the SSD nanochannel is calculated at a bias voltage 3.0 V and plotted in Fig. 3. Oscillations in both time and space domains are clearly observed. The charge domains form at the left entrance of the nanochannel and grow as they propagate to the right exist. Whenever one domain exits the nanochannel, another charge domain forms at the left entrance, which results in periodical changes in the channel current. The maximum carrier concentration of the charge domain is over five times that at equilibrium, indicating a very pronounced Gunn effect. Our previous study showed that up to 90% of electrons in the SSD nanochannel can transfer from the \( \Gamma \) valley to \( L \) valley, which leads to significant slow down of the electrons due to the \( \sim 0.6 \text{ eV} \) potential energy increase and higher effective electron mass.\(^{10}\) The drastic reduction in electron velocity causes the formation of charge domain, and hence Gunn oscillations.

To study whether the asymmetry of the nanochannel plays a role in the generation of the Gunn oscillation, we also studied a symmetric nanochannel structure, as shown in Fig. 1(b). Figure 2 also shows its channel current (dashed curve) when the applied dc bias changes from 2.5 to 3.0 V at time zero. Although the dimensions of the channel width and length of the two devices in Fig. 1 are exactly the same, the dynamic responses significantly differ. For the symmetric structure, the current is lower due to the lack of the self-switching effect. The induced oscillating current quickly damps to zero within a few periods. We have also checked other voltages from 0 to 3.5 V but no sustained Gunn oscillations are observable. Two factors may be responsible for generation of the Gunn oscillations seen in the SSD simulations. First of all, the asymmetric boundary conditions of the SSD result in a strongly nonuniform distribution of electric field along the nanochannel,\(^{10}\) which is a favorable condition for Gunn oscillation. The effective electron channel in the
SSD is also widened by a positive bias but not in the case of the symmetric device. This particularly occurs around the left entrance of the nanochannel due to the strongest transverse electric field, which allows more electrons to flood into the nanochannel to form charge domains.

It is worth noting that a conventional Gunn diode typically exhibits a negative differential resistance in the current-voltage characteristic. However, only a negative differential velocity is required to generate a slow down of carriers and hence formation of a carrier domain for Gunn oscillations. In the SSD, pronounced negative differential velocity has been shown in Figs. 3 and 4 in Ref. 10. There is no negative differential resistance because an increased forward biased voltage also induces more carriers inside the channel due to the increased transverse electric field (see Fig. 4 in Ref. 10).

It is worth noting that a large array of SSDs can be fabricated in parallel with one another in a single step of nanolithography without the need for interconnection.6,15 In such a case, the impedance of the overall device will be favorably reduced. More importantly, the output power can be enhanced by a factor at least equal to the number of SSDs or even more if there is any phase locking of the oscillations in individual nanochannels. It is also possible to make the individual SSDs with different nanochannel widths so as to generate different oscillation frequencies on a single chip. The feasibility of switching on and off each individual SSD separately may make it convenient for terahertz spectroscopy studies. This is something that a conventional vertical Gunn diode structure is difficult to achieve since the oscillation frequency is largely fixed by a given semiconductor wafer. The planar architecture also allows radiation naturally along the normal direction of the device surface due to the in-plane oscillating electric field. This allows for coupling of a suitable antenna to the device to assist the radiation.

The ease of heat dissipation also makes GaN Gunn diode more feasible. Although different designs have aimed to increase the frequency limit of (In)GaAs and InP Gunn diodes, GaN is more promising to achieve terahertz operations, owing to its shorter energy-relaxation time and a much higher electron saturation velocity.20,21 Despite the potential to achieve much higher frequencies and output powers than GaAs, one of the most challenging issues for practical GaN-based Gunn diodes is to deal with the heat dissipation, which could be well beyond 100 kW/cm²—a few orders of magnitude higher than GaAs devices. Because of the narrow one-dimensional-like channel of the SSD and hence much lower current than in a 2D vertical device, the heating of the device is much lower and hence much more feasible to manage. It can also be envisaged that the planar architecture allows easier design for heat dissipation, making terahertz gigahertz Gunn diode particularly promising.

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