Efficiency and harmonic enhancement trends in GaN-based Gunn diodes: Ensemble Monte Carlo analysis
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Gallium nitride can offer a high-power alternative for millimeter-wave Gunn oscillators. Hence, an ensemble Monte Carlo-based comprehensive theoretical assessment of efficiency and harmonic enhancement in $n$-type GaN Gunn diodes is undertaken. First, the effects of doping notch/mesa and its position within the active channel are investigated which favors a doping notch positioned next to cathode. It is then observed that the width of the notch can be optimized to enhance the higher-harmonic operation without degrading its performance at the fundamental mode. Next, the effects of dc bias and channel doping density are investigated. Both of these have more significant effects on the higher-harmonic efficiency than the fundamental one. The lattice temperature is observed to have almost no influence up to room temperature but severely degrades the performance above room temperature. As a general behavior, the variations of temperature, channel doping, and the notch width primarily affect the phase angle between the current and voltage wave forms rather than the amplitude of oscillations. Finally, the physical origin of these Gunn oscillations is sought which clearly indicates that the intervalley scattering mechanism is responsible rather than the $\Gamma$ valley nonparabolicity or the effective mass discrepancy between the $\Gamma$ and the lowest satellite valleys. © 2004 American Institute of Physics. [DOI: 10.1063/1.1812376]
A single-tone sinusoidal voltage of the form $V_{dc} + V_{ac} \sin(2\pi ft)$ is imposed across the structure; if not stated, we use $V_{dc} = 60$ V and $V_{ac} = 15$ V. This choice significantly simplifies our frequency performance assessment. Moreover, its validity was checked by relaxing the imposed single-tone sinusoidal voltage across the Gunn diode and connecting it to an external tank circuit with the voltage across the device being self-consistently updated at each simulation step through solving the Gunn diode and the external circuit. For both cases, the phase relations were found to be very similar. To assure that both amplitude and phase have stabilized, simulations are lasted for at least 0.2 ns. The current waveform is sampled at every 80 fs while the simulation time step is 0.4 fs.

The oscillator efficiency, is defined as $\eta = P_{ac}/P_{dc}$, where $P_{ac}$ is the time-average generated ac power and $P_{dc}$ is the dissipated dc power by the Gunn diode. First, the effect of the doping notch width [positioned next to cathode, c.f. Fig. 1(a)] is investigated. It is observed that there is an optimum notch width, for our case, around a value of 80 nm, at which the second-harmonic efficiency approaches that of the fundamental mode value as seen in Fig. 2(a). However, we would like to point out that the value of the optimum notch width is sensitive to the material parameters and our previous analysis with the bandstructure data of Ref. 10 resulted in a wider width. On the other hand, a doping mesa rather than a notch was suggested to enhance the harmonic content of the current waveform. To elucidate this point, Fig. 2(b) compares the performance of four configurations made from the combinations of notch/mesa placed next to cathode and in the middle of the active region. It is seen that notch placed next to cathode (labeled as 1) performs the best among all. A source of curiosity regarding Fig. 2(b) is the substantial frequency shift for the notch placed in the middle (labeled as 3) and mesa placed next to the cathode (labeled as 2). A detailed time-domain investigation of these structures shows that for both cases almost half of the active region is inactive in the domain nucleation processes, hence remarkably decreasing the transit time of the Gunn domains.

In Fig. 3, the effects of dc bias and channel doping are displayed. While changing the applied dc voltage, we need to scale the rf amplitude accordingly not to lose the grounds for efficiency comparison. The applied dc voltage has to be above a critical value so that the device is biased in the negative differential mobility regime. Therefore, increasing bias has favorable effect on the fundamental and harmonic efficiencies. The channel doping on the other hand is relatively less influential on the fundamental mode efficiency than the higher harmonic modes, so that for a given notch width and bias voltage, there is an optimum channel doping that favors the harmonic enhancement. However, there is a
lower threshold for the channel doping as it determines the dielectric domain nucleation time that needs to be much shorter than the domain transit time through the active region.

For high power Gunn diodes, thermal heating can be an important issue. At the expense of neglecting thermal gradient effects, we simply consider the uniform lattice temperature effects on the efficiency. As can be observed in Fig. 4(a), up to room temperature, there is no sensible variation, whereas above the room temperature performance increasingly degrades becoming passive above 480 K in the case considered. The source of this degradation is not due to a reduction in the oscillation amplitudes but rather due to phase angle difference between the current and voltage waveforms, and efficiency; 80 nm-notch device at 60 V bias and its fundamental frequency (160 GHz) is used. (b) rf conversion efficiency and frequency for several lattice temperatures; 80 nm-notch device at 60 V bias is used.

FIG. 4. (Color online) (a) Temperature vs phase angle, $\theta_{ph}$, between the current and voltage wave forms, and efficiency; 80 nm-notch device at 60 V bias and its fundamental frequency (160 GHz) is used. (b) rf conversion efficiency and frequency for several lattice temperatures; 80 nm-notch device at 60 V bias is used.

In summary, we have analyzed the trends in efficiency and harmonic enhancement in GaN Gunn diodes under doping profile, bias, and temperature variations. The key parameter in all these efficiency considerations has been the phase angle difference between the current and voltage waveforms. Our extensive simulations indicate that the carrier dynamics in GaN can be tailored by an optimum choice of doping profile, temperature, and bias conditions so that the efficiency of higher harmonic Gunn oscillations can be boosted.

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