Temperature Behavior of Gunn Oscillations in Planar InGaAs Diodes

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***Abstract*— Planar Gunn diodes on $In_{0.53}Ga_{0.47}As$ with lengths between 2 and 5 μm have been fabricated and characterized in a temperature range of 10 to 300 K. Two different oscillation regimes are observed depending on temperature. At the higher values, the frequency of the oscillations decreases as the bias increases, as expected for a well-established transit-time domain mode. But below approximately 75 K, the behavior is the opposite, the frequency of the Gunn oscillations increases with the bias. This fact, together with a much lower amplitude of the oscillations, indicate the possible switch to a different oscillation mode in which the domains are not able to attain their complete maturation before reaching the anode.**

***Index Terms*— Gunn effect, planar Gunn diodes, InGaAs.**

I. Introduction

GUNN diodes (GDs) are one of the most popular technologies for the realization of microwave oscillators due to their simplicity and low-voltage operation. GDs are at the base of RF power sources, often multiplied by using chains of Schottky barrier diodes (SBDs), but they also work as local oscillators (LOs) for heterodyne transmitters and receivers in wireless communication systems and high-frequency power detectors [1]. Even if material properties seemed to impose fundamental frequency limits on InP based GDs of approximately 200 GHz, [2] they can be overcome by means of optimized device structures with improved heat dissipation and RF power extraction at the second or higher harmonic frequencies, so that submillimeter-wave frequencies above 300 GHz can be reached [3]. Moreover, taking advantage of the sub-harmonic architecture and the low-parasitic SBD technology, heterodyne detectors have been able to reach the THz range [4]. High power LOs can be obtained with high-frequency power amplifiers or combining frequency multipliers [5] at the expenses of increasing the complexity of the RF source. The development of planar Gunn diode (PGD) technology would allow for increasing the power of LOs with a simple architecture and easy integration with SBD technology [6]–[8]. Cryogenic operation of heterodyne detectors is often used for decreasing their noise temperature at THz frequencies, so that the characterization and understanding of the low-temperature operation of such planar Gunn oscillators is of high interest. In this work we analyze the performance of InGaAs based PGDs as a function of T from 10 to 300 K, with the characterization process described in Ref. [10].

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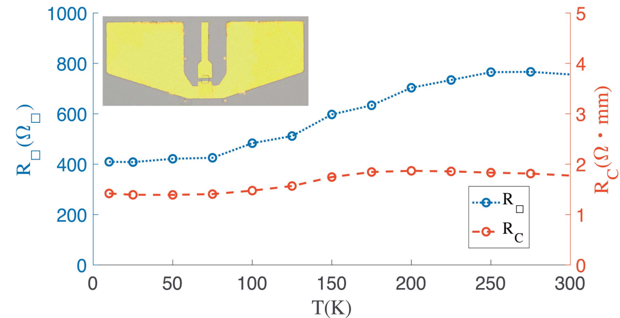

Fig. 1. R_C and $R_\square$ vs. T extracted with TLMs of 20 μm wide mesas. The inset shows a microscope picture of the PGD under test.

II. Measurements: DC and RF Results

The PGDs under study, as in Ref. [10], are based on the epilayer design of Ref. [7], consisting in two $In_{0.53}Ga_{0.47}As$ active layers, a 50 nm thick cap layer with n-doping of 2×10^{18} cm^{-3} on the top of a 100 nm layer doped at 8×10^{16} cm^{-3}, grown on an InP substrate. 12×12 μm mesa were first defined with a Cl_2/BCl_3 based ICP-RIE dry etching process. Then, Ti/Au (2/50 nm) ohmic contacts were fabricated with separations between 2-5 μm.

A value of the ohmic contact resistance around $R_C = 750\ \Omega_\square$ and a square resistance around $R_\square = 2\ \Omega$.mm were obtained at room temperature by means of TLM measurements, Fig.1. R_C is not very low since no annealing process of the ohmic contacts was made, but enough for a correct operation of the PGDs. When lowering T, the cables and probe contacting resistance increases, compensating the decrease of $R_\square$ down to 400 $\Omega_\square$, so that the apparent resistance of the measured I-V curves of the PGDs is fairly constant with T (see Fig. 2).

The devices have been characterized in DC and RF in a temperature range between 10 and 300 K using a Lakeshore CRX-VF cryogenic probe station. DC measurements were

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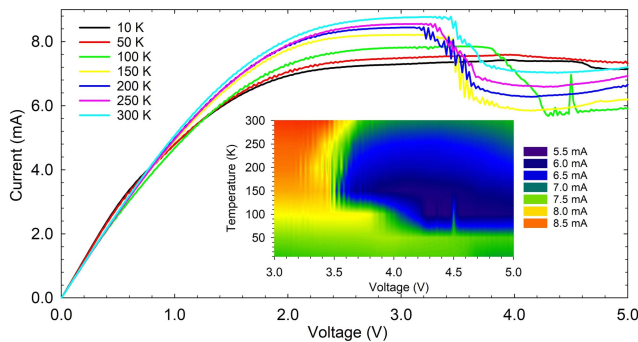

Fig. 2. *I-V* curves of a PGD with a 4 μm contact separation and 20 μm width in the temperature range from 10 K to 300 K. The inset shows the same values represented with a colour map.

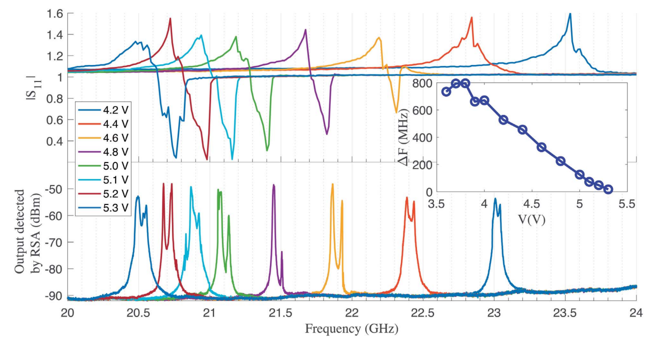

Fig. 3. Comparison between a) $|S_{11}|$ and b) output power measured with the VNA and RSA, respectively, for the PGD with 4 μm contact separation at different bias and 300 K. The inset shows the frequency shift between the peaks observed in both quantities.

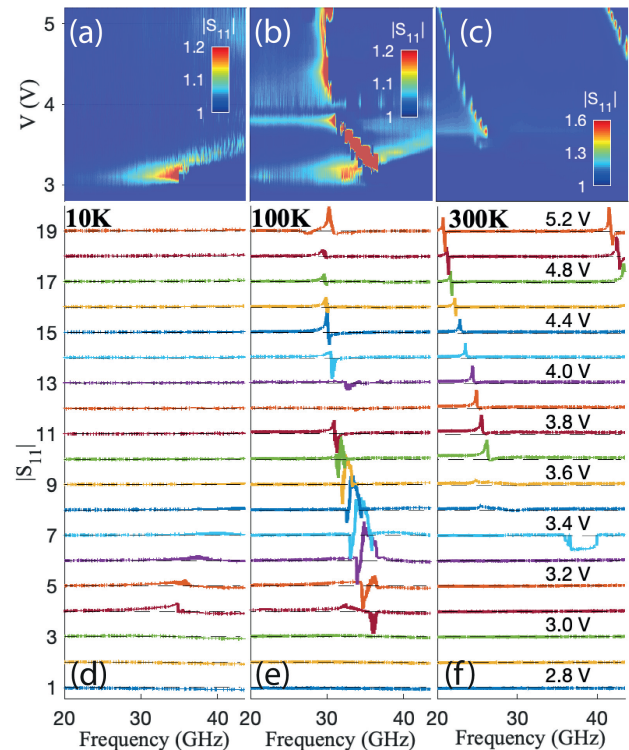

Fig. 4. $|S_{11}|$ vs. frequency for different bias (voltage step of 0.1 V for $V < 4.0$ V, and 0.2 V for $V > 4.0$ V, an offset of $+1$ was added to each curve) at (d) 10 K, (e) 100 K and (f) 300 K. (a), (b) and (c) are colour maps corresponding to plots (d), (e) and (f), respectively.

performed using a Keithley 4200 semiconductor parameter analyzer, which was also used for biasing the devices while performing the RF measurements with an Agilent N5244A PNA-X vector network analyzer (VNA) and a Tektronix RSA5126A real time spectrum analyzer (RSA) [10], which allow to reach 43.5 and 26.5 GHz, respectively. In order to precisely obtain the values of the scattering parameter S_{11}, the cables and probes were calibrated for each temperature, and were obtained by averaging 10 consecutive frequency sweeps of the VNA (6 for the measurements performed with the RSA).

Fig. 2 shows the measured *I-V* curves for a diode with a 4 μm distance between contacts. As observed, the low-voltage region does not change much when decreasing the temperature from 300 to 10 K, providing a value of the ohmic resistance which is nearly constant around 200 Ω. In contrast, the saturation current is much affected by the temperature, decreasing more than 20 % from about 8.5 to 6.5 mA, when lowering T from 300 to 10 K. The current drop observed in the *I-V* curves, with the associated negative differential resistance (NDR), clearly evidences the onset of Gunn oscillations (GOs), mainly at high temperatures. The threshold voltage for which the NDR appears slightly decreases from around 3.5 V@300 K to 3.2 V@200 K, as expected, since phonon scattering is less effective and the onset of GOs shifts to lower bias. But, unexpectedly, when decreasing the temperature below 200 K the NDR appears for higher voltages (as observed in the colour map of the inset of Fig. 2). However, we have to remark that there is not a perfect correlation between the current drop and the onset of GOs. Indeed, at low temperatures, GOs emerge for biases much below the appearance of the NDR. For example, @100 K GOs are visible starting from around 3.0 V, while the threshold for NDR is near 4.0 V. Additionally, below 50 K, the NDR is very weak, probably due to a low amplitude of the GOs.

The RF characterization of the fabricated InGaAs PGDs was performed by using two different instruments: VNA and RSA [10]. A remarkable consistency between both was found, as shown in Fig. 3 for $T = 300$ K. At high enough bias, above the threshold voltage needed for the onset of GOs, V_{th}, the RSA detects that some RF power is generated by the diode. In such conditions $|S_{11}|$ takes values above the unity, meaning that the device is active. Moreover, when GOs are stable, $|S_{11}|$ shows a kind of resonant behaviour, with its maximum values corresponding to the frequency at which the RF power is generated [10], but also taking negative values at frequencies above that of the self-sustained GOs. When GOs are not stable (for applied biases just above V_{th}, 3.5-4.0 V) there is a slight shift between the maximum power emission measured by the RSA and the peak of $|S_{11}|$ (which does not show the negative part of the resonance), but always falling inside the range where $|S_{11}| > 1$. The misalignment between both peaks, plotted as a function of the bias in the inset of Fig. 3, takes a value of about 800 MHz just above V_{th}, and decreases as the applied bias increases, vanishing when GOs become stable.

The behavior of $|S_{11}|$ in the temperature range 10-300 K is shown in Fig. 4. The first harmonic of the GOs is detected at

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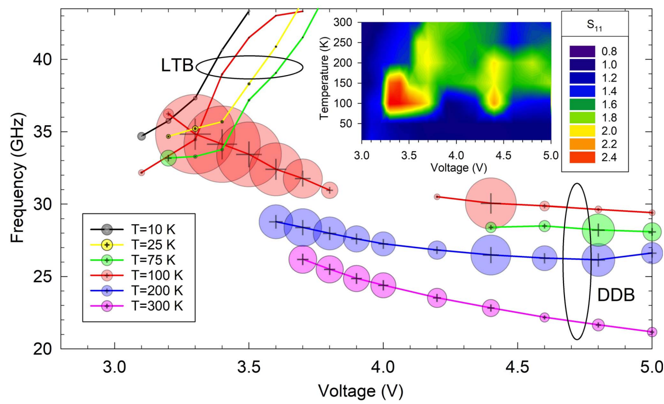

Fig. 5. Frequency and amplitude (indicated by the bubble size and also represented as a colour map in the inset) of the maximum of $|S_{11}|$ as a function of bias for several temperatures.

300 K but not at lower T due to the frequency limitations of our experimental system (43.5 GHz). The main result of Fig. 4 is that the behaviour of the GOs at T below 100 K is much different from that found at 300 K. A similar behaviour has also been observed in the rest of diodes with different contact separations L, with a threshold voltage for the onset of the oscillations approximately proportional to L and oscillation frequencies proportional to $1/L$.

At 300 K, Fig. 4(c) and (f), the frequency of GOs decreases as the bias increases above V_{th}, as expected from the reduction of the drift velocity of the dipole domains when the electric field increases. This appears in the colour map of $|S_{11}|$, Fig. 4(c) as a "classic" dipole-domain branch (DDB) of GOs (and its first harmonic), oriented versus the top left corner of the graph. While other works on InGaAs PGDs find unexpectedly high oscillation frequencies [7], instead, our devices oscillate at around 20-25 GHz at 300 K within the DDB, in good agreement with the theoretical value of the saturation velocity of InGaAs, approximately 10^5 m/s [9], [10].

At T below 100 K, a different behaviour is observed, a "low-T branch" (LTB) of GOs appears, at a frequency which increases fast with the bias and showing a much broader spectrum. Both branches are superimposed for 100 K, thus providing a constructive mechanism, which leads to high amplitude oscillations at the crossing point (around 35 GHz at 3.3 V). This is better observed in Fig. 5, which clearly shows that the optimum conditions for obtaining high amplitude GOs are found in the 100-150 K range for bias around 3.4-3.5 V, where the LTB constructively coincides with the highest oscillation frequencies of the classic DDB at around 35 GHz. This enhanced oscillation frequency could be associated with an increased Gunn domain velocity, which would theoretically correspond to 1.4×10^5 m/s (as compared to 1.1×10^5 m/s obtained at 300 K) [10]. However, these faster GOs are more likely due to an increase of the dead zone, and the associated decrease of the effective transit length as the domain formation takes place closer to the anode.

Fig. 5 shows that the DDB, as expected, moves to much higher frequencies when decreasing T due to the increase of the Gunn domain drift velocity, until disappearing below 100 K. Additionally, V_{th} favourably decreases when lowering T, from around 3.7 V at 300 K to around 3.3 V at 100 K, due to a weakened action of phonon scattering. The behaviour of the GOs within the LTB is completely different, not only because of the opposite bias dependence of the oscillation frequency, but also because of the much lower amplitude and worse frequency purity.

This means that the oscillation mechanism in the LTB is not that of a classic well-formed dipolar domain. We attribute the high oscillation frequencies (and their increase with the bias) of the LTB to the formation of domains close to the anode (closer as the bias increases), not able to reach their complete maturation before reaching the contact. Therefore, the frequency of GOs in the LTB is much higher than in the DDB, for which the domains build up near the cathode and take much longer time to transit the device and disappear. We have to remark that this mechanism is different from the well known quenched-domain GO mode [11], where higher oscillation frequencies are achieved by the quenching of the domains forced by an external resonant circuit which reduces the applied voltage before the complete nucleation of the domains is reached.

What we observe at low T is due to the shifting of the domain formation zone to the region near the anode, so that the dipole domains do not have enough space to mature. Therefore, the frequency of the LTB is much higher than that of classic GOs, for which the domains build up near the cathode and take much longer time to transit the device and disappear. This happens because at low T, when phonon scattering is reduced, the high field region arising near the anode is enough for the onset of the domain formation, even if the starting point is not always located at the same position, thus originating quite a broad frequency spectrum of generated power. This explanation is coherent with the fact that the amplitude of the GOs within the LTB is much lower than that found in the classic DDB, and also the NDR observed in the I-V curves is much lower in the temperature range where only the LTB appears (below 75 K), features which are common with the circuit quenched-domain mode of standard GDs [12] where also the complete nucleation of the domains is not reached. Indeed, the LTB does not manifest so clearly for longer diodes, probably due to the fact that Gunn domains have more space to develop completely.

III. Conclusion

By fabricating and characterizing InGaAs PGDs we have demonstrated that their performance can be enhanced by operating them at low T. At 100 K the oscillation frequency increases to 35 GHz@3.3 V (as compared to 26 GHz@3.7 V at 300 K) with enhanced amplitude. We have also observed than an additional oscillation mode appears for $T < 100$ K, generating a LTB of GOs whose frequency is much higher than that of the classic transit-time dipole-mode operation and increases with the bias. However, even if oscillation frequencies above 40 GHz are obtained in this LTB, their amplitude is quite small, indeed much smaller than what could be obtained by selecting higher harmonics of the DDB.

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REFERENCES

[1] A. Maestrini, J. Ward, G. Chattopadhyay, E. Schlecht, and I. Mehdi, "Terahertz sources based on frequency multiplication and their applications," *Frequenz*, vol. 62, nos. 5–6, pp. 118–122, Jun. 2008.

[2] P. A. Rolland, M. R. Friscourt, D. Lippens, C. Dalle, and J. L. Nieruschalski, "Mm-wave solid-state power sources terahertz sources based on frequency multiplication and their applications," in *Proc. IEEE Int. Workshop Millim. Waves*, 1986.

[3] H. Eisele and R. Kamoua, "Submillimeter-wave InP gunn devices," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 10, pp. 2371–2378, Oct. 2004, doi: 10.1109/TMTT.2004.835974.

[4] A. Maestrini, L. Gatilova, J. Treuttel, Y. Jin, A. Cavanna, D. M. Melgar, T. Vacelet, A. Feret, S. Caroopen, G. Gay, F. Dauplay, J.-M. Krieg, B. Thomas, P. de Maagt, and C. Goldstein, "The 1200GHz receiver frontend of the submillimetre wave instrument of ESA JUpiter ICy moons explorer," in *Proc. 43rd Int. Conf. Infr., Millim., THz Waves (IRMMW-THz)*, Sep. 2018, pp. 1–2, doi: 10.1109/IRMMW-THz.2018.8509935.

[5] I. Mehdi, B. Thomas, R. Lin, A. Maestrini, J. Ward, E. Schlecht, J. Gill, C. Lee, G. Chattopadhyay, and F. Maiwald, "High power local oscillator sources for 1-2 THz," *Millim., Submillimeter, Far-Infr. Detectors Instrum. Astron.*, vol. 7741, pp. 320–325, Jul. 2010, doi: 10.1117/12.857790.

[6] M. I. Maricar, A. Khalid, G. Dunn, D. Cumming, and C. H. Oxley, "Experimentally estimated dead space for GaAs and InP based planar gunn diodes," *Semicond. Sci. Technol.*, vol. 30, no. 1, Nov. 2014, Art. no. 012001, doi: 10.1088/0268-1242/30/1/012001.

[7] A. Khalid, G. M. Dunn, R. F. Macpherson, S. Thoms, D. Macintyre, C. Li, M. J. Steer, V. Papageorgiou, I. G. Thayne, M. Kuball, C. H. Oxley, M. M. Bajo, A. Stephen, J. Glover, and D. R. S. Cumming, "Terahertz oscillations in an $In_{0.53}Ga_{0.47}As$ submicron planar Gunn diode," *J. Appl. Phys.*, vol. 115, no. 11, Mar. 2014, Art. no. 114502, doi: 10.1063/1.4868705.

[8] M. I. Maricar, A. Khalid, D. R. S. Cumming, and C. H. Oxley, "Extraction of second harmonic from an InP based planar gunn diode using diamond resonator for milli-metric wave frequencies," *Solid-State Electron.*, vol. 116, pp. 104–106, Feb. 2016, doi: 10.1016/j.sse.2015.12.001.

[9] S. Karishy, P. Ziadé, G. Sabatini, H. Marinchio, C. Palermo, L. Varani, J. Mateos, and T. Gonzalez, "Review of electron transport properties in bulk InGaAs and InAs at room temperature," *Lithuanian J. Phys.*, vol. 55, no. 4, pp. 305–314, Jan. 2016, doi: 10.3952/physics.v55i4.3228.

[10] Y. Lechaux, I. Ìñiguez-de-la-Torre, J. A. Novoa-López, Ó. García-Pérez, H. Sánchez-Martín, J. F. Millithaler, D. Vaquero, J. A. Delgado-Notario, V. Clericò, T. González, and J. Mateos, "Comprehensive characterization of Gunn oscillations in $In_{0.53}Ga_{0.47}As$ planar diodes," *Semicond. Sci. Technol.*, vol. 35, no. 11, Sep. 2020, Art. no. 115009, doi: 10.1088/1361-6641/abab1f.

[11] J. E. Carroll, "Oscillations covering 4 Gc/s to 31 Gc/s from a single Gunn diode," *Electron. Lett.*, vol. 2, no. 4, p. 141, 1966, doi: 10.1049/el:19660113.

[12] D. D. Khandelwal and W. R. Curtice, "A study of the single-frequency quenched-domain mode Gunn-effect oscillator," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-18, no. 4, pp. 178–187, Apr. 1970, doi: 10.1109/TMTT.1970.1127187.

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