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Enhanced Terahertz Detection in Resonant Tunnel Diode-Gated HEMTs

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We report our studies on terahertz detection in high electron mobility transistors (HEMTs) with a resonant-tunneling gate structure, which exhibits negative differential conductance (NDC) from gate to channel; namely, resonant-tunnel-diode (RTD) gated HEMTs. The effect of NDC on detector responsivity is theoretically derived based on Dyakonov-Shur electron-plasma wave theory. The positive gate conductance in traditional HEMTs damps the electron plasma waves, therefore reducing responsivity; conversely, in devices employing NDC gates, detector sensitivity can be greatly enhanced. Our analysis also demonstrates that resonant detection, thus high responsivity, can be obtained even near the threshold voltage in RTD-gated HEMTs, while only non-resonant detection is attainable in conventional HEMTs in this bias regime. Numerical exploration of the design space for GaN HEMTs with double-barrier AlGaN/GaN/AlGaN RTD gates is performed, showing that thin barriers with low Al composition may be the most practical structures to demonstrate this enhanced detection mechanism.

Introduction

The past decades have seen increasingly rapid advances in the field of terahertz (THz) research (1). In this context, investigation of emitters and detectors has been one of the most dynamic areas, aiming for applications including astronomy, biomedicine, communications, and defense (2). Dyakonov and Shur's theory (3) states that electrons in a high electron mobility transistor (HEMT) behave as a two dimensional electron fluid (2DEF) and thus can be described by a hydrodynamic model. As a consequence, electron-plasma waves, which can propagate at velocities much larger than those of electrons limited by their drift saturation velocity, may be excited in the channel. Several studies have shown that this phenomenon can result in efficient detection, generation, and frequency multiplication of THz radiation; experimental demonstrations of THz detection have been reported in Si (4), GaAs (5), and GaN (6) based transistors. However, the detector responsivities experimentally obtained so far have been modest (~$1\text{x}10^3$ V/W (6)) in comparison with the very high responsivities theoretically predicted. In the previous analytical and experimental studies (7-8) it was reported that the gate leakage current is primarily responsible for the low responsivity. In this work, we present a comprehensive study on how to enhance responsivity using device structures with gates exhibiting negative differential conductance (NDC). For simplicity, we have named this class of devices as resonant-tunnel-diode gated HEMTs. However, the principle shown in this work should apply to all Dyakonov-Shur devices employing gates exhibiting NDC.

The benefits of complementing electron-plasma waves with an element exhibiting NDC were previously discussed in Ref. (9). It was theoretically shown that the plasma resonance (peaks in detector responsivity) can be sharpened in a four terminal hot electron transistor device as proposed in Ref. (10), when electrons tunnel from its emitter (a 2DEF region) to a collector by resonant tunneling through a double barrier structure. In this paper we present a theory that is not restricted to any specific device topology, and therefore a generalization of the previous result. Based on our theory, we further show that resonant response in our proposed RTD-gated HEMTs is possible even when the device is biased near threshold, where traditional devices operate only in a non-resonant mode. Design space exploration is performed in the GaN material system since GaN promises high frequency THz detection due to its higher maximum achievable 2D carrier concentration in comparison with other semiconductors (8). Our study shows that RTD gates using thin barriers with low Al composition might be the most practical structures to demonstrate this enhanced detection mechanism.

Hydrodynamic model

The equations that govern the electron transport in the channel of a HEMT as described by the hydrodynamic model (3) are given by:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}+\frac{e}{m}\frac{\partial U}{\partial x}+\frac{v}{\tau}=0, \qquad [1]$$

$$\frac{\partial n}{\partial t}+\frac{\partial (nv)}{\partial x}=\frac{j_z(x)}{e}, \qquad [2]$$

where Eqn.[1] is the Euler equation, and Eqn.[2] corresponds to the classical continuity equation (also including the effect of gate leakage as I_z). Note that in these equations e is the absolute value of electron charge, m is electron conduction effective mass, τ the electron relaxation time, v is the electron velocity, n is the 2D electron channel concentration, the potential $U=U_{gc}-U_{th}$, and $j_z(x)=I_z(x)/WL$ where W is the transistor width and L the channel length. j_z is defined as positive when the current is flowing out of the channel (electron flux towards the channel).

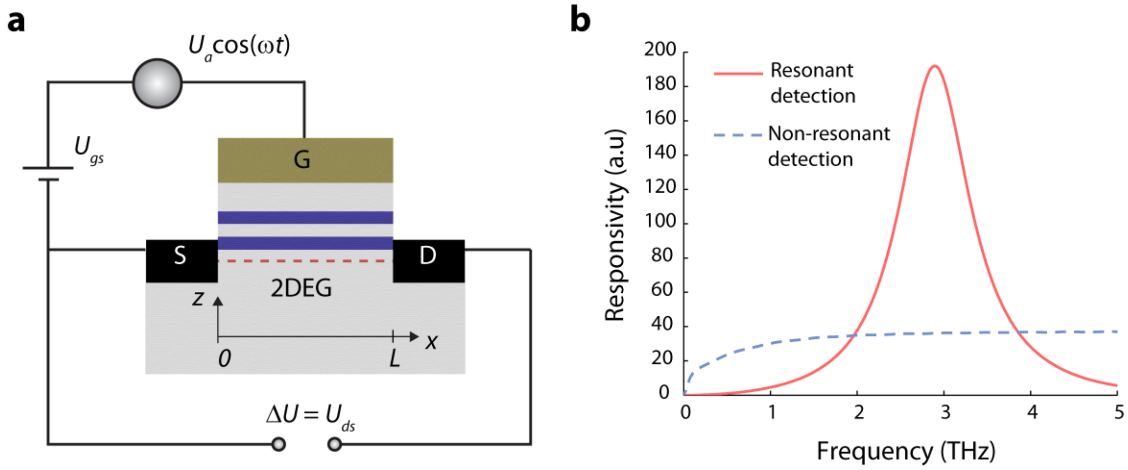

Figure 1. a) Device structure and biasing configuration; a THz signal is applied between gate and source, drain is left open both in DC and RF. b) Typical responisivities for resonant and non-resonant detector configurations.

Response well above threshold

Let's consider a self aligned HEMT biased as shown in Fig. 1a. For now it will be assumed that the gate voltage bias (DC) is such that $U_{gs} >> U_{th}$, but this assumption will be later relaxed in order to analyze the case when the transistor is biased near threshold. In addition, AC and DC open boundary conditions will be considered at the drain terminal. Also it will be assumed that the induced DC voltage U_{ds} is much smaller than $U_{gs} - U_{th}$ (detected voltage is small in relation to the gate bias overdrive); this is a logical assumption if the transistor is biased well above U_{th} (forward biased), which is normally the case for resonant THz detection. Therefore the boundary conditions (AC) at source ($x = 0$) and drain ($x = L$) are given by:

$$\begin{aligned} &U(0,t) - \langle U(0,t) \rangle = U_a \cos(\omega t) \quad x = 0 \\ &v(L,t) = 0 \quad x = L \end{aligned} , \qquad [3]$$

where $\langle \cdot \rangle$ represents time average, $U_0 = \langle U(0,t) \rangle$ is the DC gate voltage swing and $U_a \cos(\omega t)$ is the induced AC voltage by the THz radiation.

Since we are assuming that the transistor is forward biased, the gradual channel approximation is valid and consequently Eqn. [2] can be rewritten as:

$$\frac{C_{gate}\, m}{e} \left(\frac{\partial u}{\partial t} + \frac{\partial (uv)}{\partial x} \right) = j_z(x), \qquad [4]$$

where C_{gate} is the gate capacitance and considered as constant with respect to the spatial coordinate x because $U_{ds} << U_{gs} - U_{th}$, and u is defined as $u = eU/m$. Looking for solutions of the governing equations [1] and [4] of the form:

$$\begin{cases} u = \bar{u} + u_1 + \ldots \\ v = \bar{v} + v_1 + \ldots \end{cases}, \qquad [5]$$

where $\bar{u}, \bar{v}$ are average value and u_n, v_n are n$^{\text{th}}$ time harmonics, the following equations are derived for the first harmonic:

$$\frac{\partial v_1}{\partial t} + \frac{\partial u_1}{\partial x} + \frac{v_1}{\tau} = 0, \qquad [6]$$

$$\frac{\partial u_1}{\partial t} + u_0 \frac{\partial v_1}{\partial x} - \left(\frac{e}{mC_{gate}} \right) \left. \frac{\partial j_z}{\partial u} \right|_{u_0} u_1 = 0 \quad . \qquad [7]$$

In this context, we define:

$$\alpha = -\left[\left(\frac{e}{mC_{gate}}\right)\left.\frac{\partial j_z}{\partial u}\right|_{u_0}\right]^{-1} = \frac{C_{gate}}{g_{gate}}, \quad s^2 = u_0 \quad , \qquad [8]$$

where g_{gate} is the gate conductance. By taking the time average of Eqns. [1] and [4], the following equations are derived for the DC components:

$$\frac{\partial}{\partial x}\left(\bar{u} + \frac{\langle v_1^2 \rangle}{2}\right) + \frac{\bar{v}}{\tau} = 0, \qquad [9]$$

$$\frac{\partial}{\partial x}\left(u_0\bar{v} + \langle u_1 v_1 \rangle\right) - \left(\frac{e}{mC_{gate}}\right)\left(j_z(u_0) + \left.\frac{\partial^2 j_z}{\partial u^2}\right|_{u_0}\frac{\langle u_1^2 \rangle}{2}\right) = 0 \ . \qquad [10]$$

By considering solutions of the form: $u_1, v_1 \propto e^{i(kx-\omega t)}$, and substituting into Eqns. [6]-[7], the following dispersion relation is obtained:

$$k = \pm k_0 = \pm s^{-1}\sqrt{\omega^2 + i\omega\left(\tau^{-1} + \alpha^{-1}\right) - \left(\tau\alpha\right)^{-1}} \ . \qquad [11]$$

It can be easily noticed from this equation that the effect of gate conductance, which is given by $1/\alpha$ adds to the damping term due to electron scattering ($1/\tau$), thereby acting in the model as a second damping element. This is the physical mechanism whereby gate leakage has been observed to degrade detector responsivity. But in cases where $\alpha = C_{gate}/g_{gate} < 0$, the damping can be counteracted, leading therefore to enhanced detector responsivity.

Following the same argument as in Ref. (3), the solution of Eqns. [6]-[7] becomes:

$$u_1 = \mathrm{Re}\left[\left(C_1 e^{ik_0 x} + C_2 e^{-ik_0 x}\right)e^{-i\omega t}\right] \quad , \qquad [12]$$

$$v_1 = \mathrm{Re}\left[\frac{\omega + i\alpha^{-1}}{k_0 u_0}\left(C_1 e^{ik_0 x} - C_2 e^{-ik_0 x}\right)e^{-i\omega t}\right] \quad , \qquad [13]$$

where

$$C_1 = u_a / \left(1 + e^{2ik_0 L}\right), \quad C_2 = u_a / \left(1 + e^{-2ik_0 L}\right). \qquad [14]$$

Then, the DC solution can be found by integrating Eqns. [9]-[10] and from it the detector response can be estimated. There are two modes of detector response: (i) a resonant mode, in which the detector response is narrowband but exhibits very high responsivity peaks at frequencies where $kL = (2n+1)\pi/4 \quad n = 1, 2, \ldots$; and (ii) a non-resonant mode where detection is broadband (see Fig. 1b). In classical HEMTs, the first mechanism (resonant detection) corresponds to a case where $\omega\tau >> 1$ and $s\tau/L >> 1$, while the second situation occurs otherwise (Ref. (3)).

Response near threshold

For analyzing the response at or near threshold we will consider our primary variables to be the electron velocity and local sheet concentration rather than the local potentials in order to simplify the problem, see Ref. (8). Near threshold, one can assume a band diagram under the gate consisting of quantized energy levels within the channel. Considering this, charge in the channel can be expressed as:

$$n_s(E_f) = \sum_i \int_{E_i}^{\infty} DOS.f(E)dE \quad , \qquad [15]$$

where $i = 1...M$ with M being the number of quantized energy levels, and DOS the 2D density of states, which is given by:

$$DOS = m^*_{DOS} / \pi\hbar^2 \quad , \qquad [16]$$

with m^*_{DOS} being the 2D DOS electron effective mass. Therefore, by taking into account the Fermi-Dirac distribution, quantum capacitance (as a function of channel concentration n_s) can be derived by assuming a single band occupation:

$$C_q = q^2 (g_v m^*{}_{DOS} / \pi\hbar^2)\left(1 - \exp\left(-n_s \pi\hbar^2 / kTm^*{}_{DOS}\right)\right) . \qquad [17]$$

Consequently, the total capacitance can be written as:

$$C_{total} = \left[C_{gate}^{-1} + C_q^{-1}\right]^{-1} \qquad [18]$$

which is a function of n_s as can be seen from Eqn. [17]. In this regime, the gradual channel approximation is not valid, but Euler's equation [1] can be easily modified by considering the effect of quantum capacitance, Eqn. [17], as:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{e^2}{mC_{total}(n_{s,0})}\frac{\partial n_s}{\partial x} + \frac{v}{\tau} = 0 \quad . \qquad [19]$$

By looking for solutions of the governing equations [19] and [2] in terms of a time averaged electron velocity and local channel concentration and their higher harmonics, the following equations are derived for the first harmonic:

$$\frac{\partial v_1}{\partial t} + \frac{e^2}{mC_{total}(n_{s,0})}\frac{\partial n_{s,1}}{\partial x} + \frac{v_1}{\tau} = 0 \ , \qquad [20]$$

$$\frac{\partial n_{s,1}}{\partial t} + n_0 \frac{\partial v_1}{\partial x} - \frac{e}{mC_{total}(n_{s,0})}\left.\frac{\partial j_z}{\partial u}\right|_{n_{s,0}} n_{s,1} = 0 \, . \qquad [21]$$

In this context, we define:

$$\beta = -\left[\frac{e}{mC_{total}(n_{s,0})} \left. \frac{\partial j_z}{\partial u} \right|_{n_{s,0}} \right]^{-1} , \qquad [22]$$

$$\xi^2 = \frac{e^2}{mC_{total}(n_{s,0})} . \qquad [23]$$

For the DC components, the following equations hold:

$$\frac{\partial}{\partial x}\left(\xi \overline{n}_s + \frac{\left\langle v_1^2 \right\rangle}{2} \right) + \frac{\overline{v}}{\tau} = 0 , \qquad [24]$$

$$\frac{\partial}{\partial x}\left(n_{s,0}\overline{v} + \left\langle n_{s,1} v_1 \right\rangle \right) - \frac{j_z(n_{s,0})}{e} = 0 . \qquad [25]$$

By considering solutions of the form: $n_{s,1}, v_1 \propto e^{i(kx-\omega t)}$, and substituting into Eqns. [20]-[21], the following dispersion relation is obtained:

$$k = \pm k_0 = \pm \frac{1}{\xi n_0} \sqrt{\omega^2 + i\omega\left(\tau^{-1} + \beta^{-1}\right) - \left(\tau\beta\right)^{-1}} . \qquad [26]$$

Now the problem can be completely solved by following exactly the same steps as described in the previous sub-section.

Results and discussion

As previously noted, from Eqn. [11] it follows that if $\alpha = -\tau$ the damping of the electron plasma waves is entirely counteracted ($\mathrm{Re}(k) = 0$). This can be rewritten as $c_{gate} / g_{gate} = -\tau$, where c_{gate} and g_{gate} represent the distributed gate capacitance and conductance, respectively. As a result, in HEMT structures exhibiting negative differential conductance (g_{gate} < 0), damping can be counteracted leading thus to enhanced detector responsivity. Considering a GaN HEMT structure with parameters: c_{gate} = 0.69 µF/cm^2, L = 150 nm, $U_0 = U_{gs,DC} - U_{th}$ = 1 V, $m = 0.2m_0$, and μ = 1400 cm^2/V.s, we obtain the responsivities presented in Fig. 2 for different values of α . It can be noticed that peak resonant responsivity increases when the effective damping is reduced (α approaches τ), but at the expense of the detector response becoming more narrowband. For $\alpha = -1.1 \times \tau$ a responsivity of 6200 V/W is calculated, with a bandwidth of 60 GHz, which is more than 75 times larger than what is achievable in the same HEMT working as THz detector but without negative differential conductance in the gate.

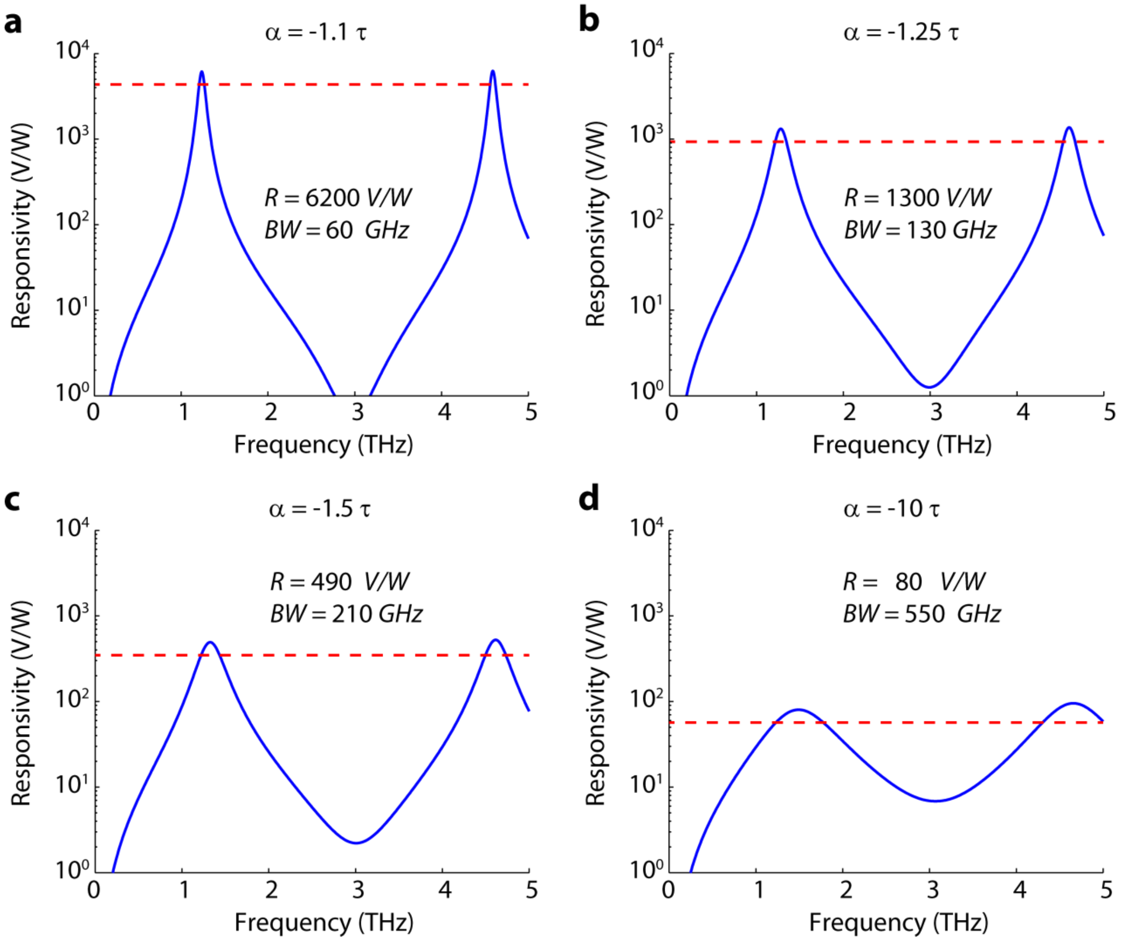

Figure 2. Calculated responsivity as a function of frequency for different values of α ($\alpha = C_{gate} / g_{gate} < 0$). When α approaches τ (a), the responsivity increases because NDC counteracts the damping of the electron plasma waves; however, the increase in responsivity is at expenses of a narrower bandwidth. When $|\alpha|$ increases, the effect of NDC becomes increasingly weak; the responsivity approaches that of the HEMT detector without a NDC gate (d). Dashed lines (red) in a)-d) indicate the responsivity levels 3dB lower than the maximum for each situation.

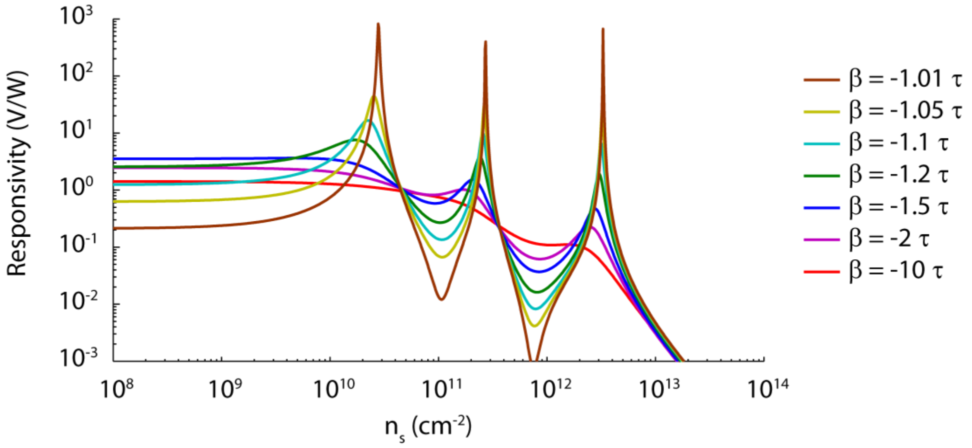

Figure 3. Calculated responsivity as a function of frequency for different values of parameter β (defined by Eqn. [22]). When β approaches τ, a resonant response is also

possible for low concentrations (near-threshold regime) in contrast to the broadband non-resonant response observed in conventional HEMTs.

Conventionally, transistors biased near threshold operate in a non-resonant detector mode (3, 8); but in devices exhibiting NDC, resonant response is also possible under these bias conditions. Responsivity is plotted for different values of β (defined by Eqn. [22]) as a function of n_s at a frequency of 1THz (see Fig. 3); from here it can be seen how resonant modes (peaks) can exist in the near-to-threshold region in the case of HEMTs with negative gate differential conductance when β approaches τ. Since the electron plasma wave characteristic frequency thus resonant detection peak can be tuned by varying n_s (Eqn. [26]), this observation suggests that it is possible to realize high responsivity in a wide range of THz frequencies using our proposed RTD-gated HEMTs.

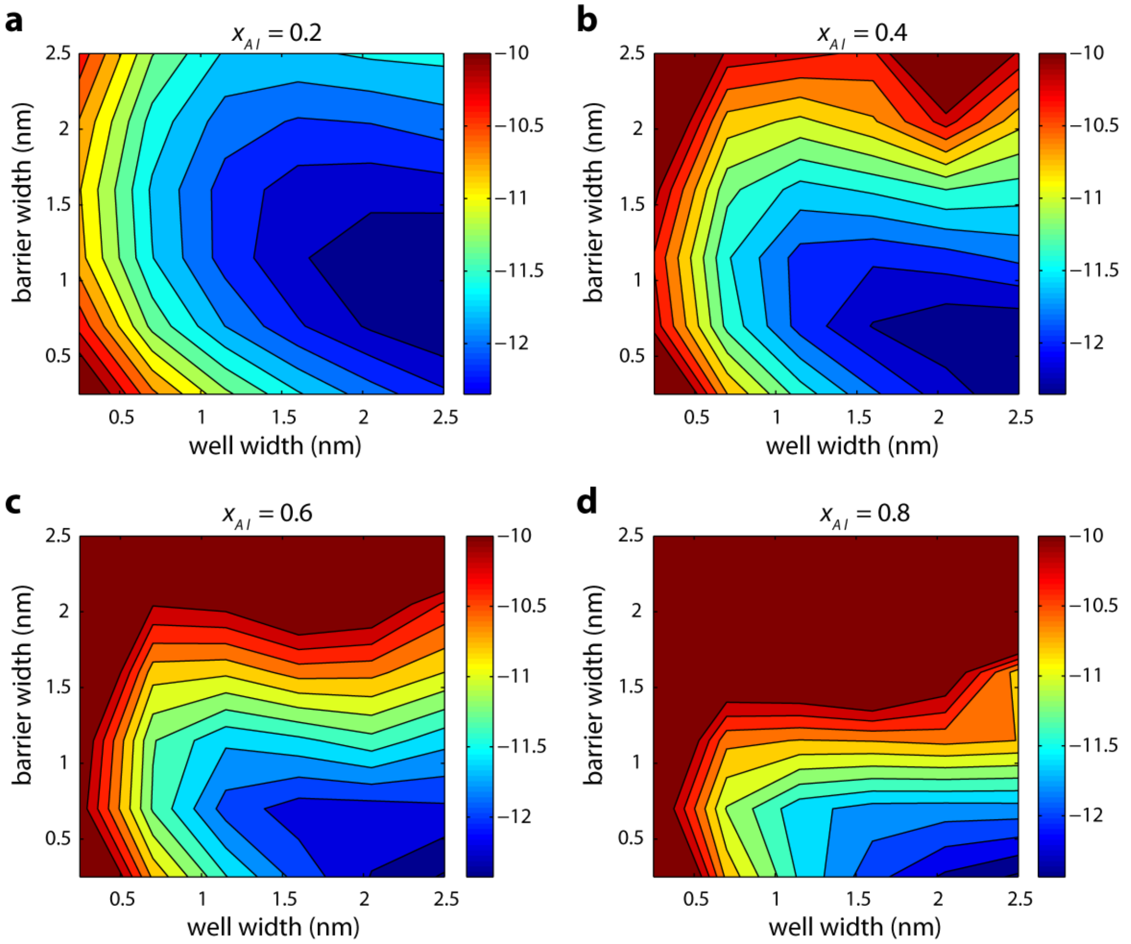

Figure 4. Calculated exponent of α ($\log_{10}$ α) as a function of well and barrier width for different Al compositions (x_{Al} = 0.2, 0.4, 0.6 and 0.8) for an AlGaN/GaN/AlGaN RTD structure. The region in which the condition for highest responsivity, α approaching τ, can be achieved is shown in dark blue.

To explore practical implementation of our proposed high responsivity devices, we investigated GaN HEMT structures with AlGaN/GaN/AlGaN double barrier gates. By systematically varying the barrier/well width and barrier height (i.e. Al composition x_{Al}), we seek a structure that meets conditions for the maximum responsivity (α approaching τ) (see Fig. 4). For this analysis, the effect of polarization field was neglected. The parameter α was obtained from computing the current as a function of voltage via the transfer matrix formalism, from where transmission probability was determined and thus tunneling current using the method described in (11). Capacitance of the RTD-structure in the gate was estimated from the serial connection of the geometric capacitance of the two tunnel barriers. We found that, for each barrier Al composition, there is a region in the barrier/well width design space that gives values of α approaching τ (in GaN $\tau \sim 0.13$ ps). The dark blue region in the plot represents this region, where maximum responsivity can be achieved. It is worth noticing that lower Al compositions allow thicker barriers, and therefore are preferred in practice for growing uniform tunnel barriers. Starting from this observation, we performed 1D Poisson simulations (12) including the effect of polarization to obtain a more accurate estimation for the capacitance. At the voltage at which g_{gate} peaks, α was determined to be around 0.04 ps (around 3 times lower than τ) for a 1nm-$Al_{0.25}GaN$ / 2nm-GaN / 1nm-$Al_{0.25}GaN$ gate stack, which allows some safety margin in real device implementation since the capacitance values measured in RTDs under peak NDR conditions are usually larger than the capacitances (13) estimated from the geometric capacitance. Therefore, we have shown that very sensitive THz detection is theoretically achievable in these practically realizable device structures.

Conclusion

We have shown that HEMT THz detectors with very high responsivity can be achieved in device structures exhibiting gate negative differential conductance. The influence of gate leakage in detector response was theoretically investigated, and it is observed that the positive gate conductance degrades the detector performance by introducing an extra damping term to the electron plasma waves. However, in structures where the gate exhibits a negative differential conductance, the electron plasma damping can be counteracted leading to enhanced detector performance. Resonant detection was shown to be possible even for gate voltage biasing near the transistor threshold voltage. Feasible device structures were also discussed, which are capable of achieving the proposed enhanced detection.

Acknowledgments

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References

1. M. Tonouchi, *Nature Photon.* **1**, 97 (2007).
2. P. Siegel, *IEEE Trans. Microwave Theory Tech.* **50**(3), 910 (2002).
3. M. Dyakonov and M. Shur, *IEEE Trans. Electron Devices* **43**(3), 380 (1996).
4. R. Tauk *et al.*, *Appl. Phys. Lett.* **89**, 253511 (2006).
5. A. V. Antonov *et al.*, *Phys. Solid State* **46**(1), 146 (2004).
6. T. Tanigawa, *et al.*, *Device Res. Conf. (DRC),* (2010).
7. W. Knap *et al.*, *J. Appl. Phys.* **91**(11), 9346 (2002).
8. B. SensaleRodriguez, *et al.*, *Int. J. High Speed Electron. Syst.* **20**(3), 597 (2011).

9. V. Ryzhii *et al.*, *J. Appl. Phys.* **88**(5), 2868 (2000).
10. A. Bonnefoi *et al.*, *Appl. Phys. Lett.* **47**(11), 888 (1985).
11. H. Mizuta and T. Tanoue, *The Physics and Applications of Resonant tunneling Diodes*, Cambridge University Press, Cambridge, (1995).
12. G. Snider, *1D Poisson/Schrödinger solver*, University of Notre Dame, Notre Dame - IN, (2012).
13. N. Shimizu, *et al.*, *Jpn. J. Appl. Phys.* **36**, 330 (1997).