Enhanced Terahertz Detection using Multiple GaAs HEMTs Connected in Series

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Abstract— **We report here, for the first time, on enhanced nonresonant detection of terahertz radiation using multiple InGaAs/GaAs high-electron-mobility transistors (HEMTs) connected in series and biased by a direct drain current. A 1.63 THz (184 μm) response is proportional to the number of detecting transistors operating in saturation region at the same gate-source bias voltage. The experimental data are in agreement with the detection mechanism based on the rectification of overdamped plasma waves excited by radiation in channels of devices.**

Index Terms— **GaAs HEMTs, series transistors, room temperature, plasma waves, short channel, terahertz detection.**

I. INTRODUCTION

Terahertz applications such as identification of drugs and explosives materials [1], medical diagnostics [2], and security imaging [3] stimulated rapid development of terahertz science and technology. THz detectors with fast response time are required for raster-scan imaging currently used in most existing terahertz imaging systems. The most common terahertz detectors available now are bolometers [4], pyroelectric detectors, Schottky diodes [5], and photoconductive detectors [6]. THz plasma wave oscillators [7]-[8], and detectors based on GaAs [9], GaN [10], Si [11], and silicon on insulator (SOI) [12] FETs have been reported. Some of these detectors demonstrated room temperature performance that is comparable to commercially available pyroelectric detectors in terms of sensitivity [13], but with a much higher speed of operation [14]-[15].

Since the first observation of plasma wave detection in short channel FETs [16], only single transistor structures (some with multiple gates) have been investigated. However, our theoretical analysis predicts dramatic enhancement of the detection responsivity in transistor arrays [17]-[18]. We now report on a multiple transistors design, in which symmetrical transistors are connected in series. Gates of all the transistors are biased separately. Drain current is driven through a battery and a load resistor to enhance the responsivity of terahertz detection [19]. We compare here the terahertz response from single transistor, two transistors, three transistors, and four transistors connected in series. Our experimental results show that detected terahertz response is proportional to the number of transistors connected in series. It also supports the conclusion that detection mechanism is based on the rectification of overdamped plasma waves excited in transistor channel [20].

II. MULTIPLE TRANSISTORS STRUCTURE

Figure 1 presents die photos of the fabricated test structures of two transistors and four transistors connected in series. The 0.5 μm enhancement-mode InGaAs/GaAs HEMT structures were fabricated by TriQuint Semiconductor. The main advantage of this technology is that it has a relatively high breakdown voltage that allows us to bias several transistors connected in series and guarantee that all of them operate in saturation region for the enhanced detection [21].

In order to test terahertz response from our multiple transistors design, radiation from a terahertz gas laser (SIFIR-50) was focused and incident normally on our test structures using the experimental setup shown in Fig. 2. Focusing of the 1.63 THz laser beam was adjusted by mounting our test structures chip on a computer controlled three dimension nanopositioning stage (NanoMax 341) from ThorLabs. The terahertz laser beam waist was measured and found to be approximately 140 μm (FWHM), while the areas of our multiple transistors design were 85×32 μm^2 for the two transistors structure and 85×50 μm^2 for the four transistors structure.

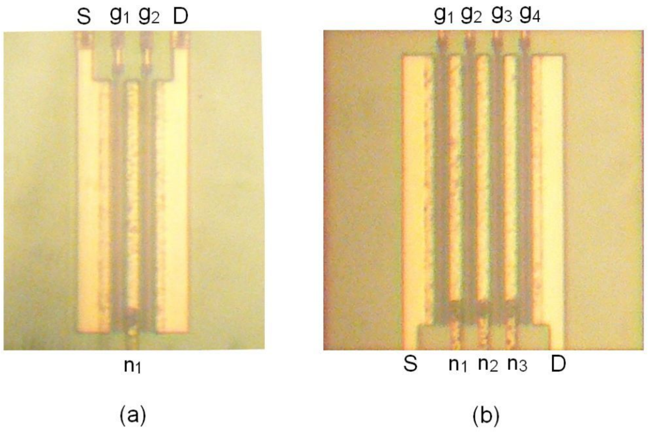

Fig. 1. Die photos of the fabricated test structures of (a) two transistors and (b) four transistors connected in series. The channel length and width of all transistors are 0.5 μm and 80 μm respectively. The separation distance between all gates is chosen to be 8 μm to be much smaller than the terahertz wavelength. All terminals are labeled showing source (S), drain (D), gates (g_1,.., g_4), and intermediate nodes (n_1,.., n_3).

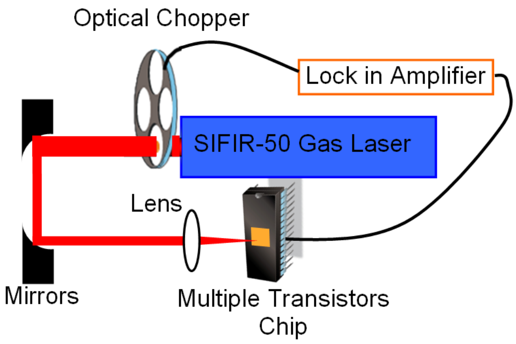

Fig. 2. Experimental setup for measuring terahertz response from our multiple transistors structure.

III. EXPERIMENTAL RESULTS AND DISCUSSION

We have tested our two transistors structure for terahertz detection in three different operating configurations. These configurations were: one transistor operated in saturation region while the other one was floating; one transistor operated in linear region and the second transistor (connected in series) operated in saturation region; and finally both transistors connected in series and operated in saturation region. Figure 3 presents the circuit schematics of the selected operating configurations showing the dc operating point at each node and dc biasing through a load resistor [22]; it also summarizes the measured responsivity for each of these configurations. The gate biasing was tuned such that each transistor detected with maximum responsivity.

Since the fraction of terahertz laser radiation coupled to our multiple transistors structure is not known precisely, the measured responsivity plots are related to terahertz laser power in arbitrary units. However, we measured the maximum power of the focused terahertz laser beam and it was found to be 35 mW. Based on this power reading, the responsivity of our two transistors structure biased as shown in Fig. 3(a) and Fig. 3(b) is estimated to be 7 V/W. while the responsivity is doubled and equal to 14 V/W when both transistors are operating in saturation region under the same gate-source biasing voltage as shown in Fig. 3(c). These estimates do not consider the much smaller area of our test structure relative to the focused laser beam waist. By considering the area ratio of the focused laser beam waist to that of each transistor in our test structure, the responsivity increases to 170 V/W independent of the number of transistors used.

The interpretation of these results is in good agreement with plasma wave THz detection theory developed in [20]. According to the mechanism described in [20], overdamped plasma waves induced by the incident radiation in the channel of FET are rectified. This results in an induction of a dc voltage between the source and the drain terminals of the transistor, i.e. the THz response. This THz response can be tuned by the gate and drain biases controlling electron density in the channel.

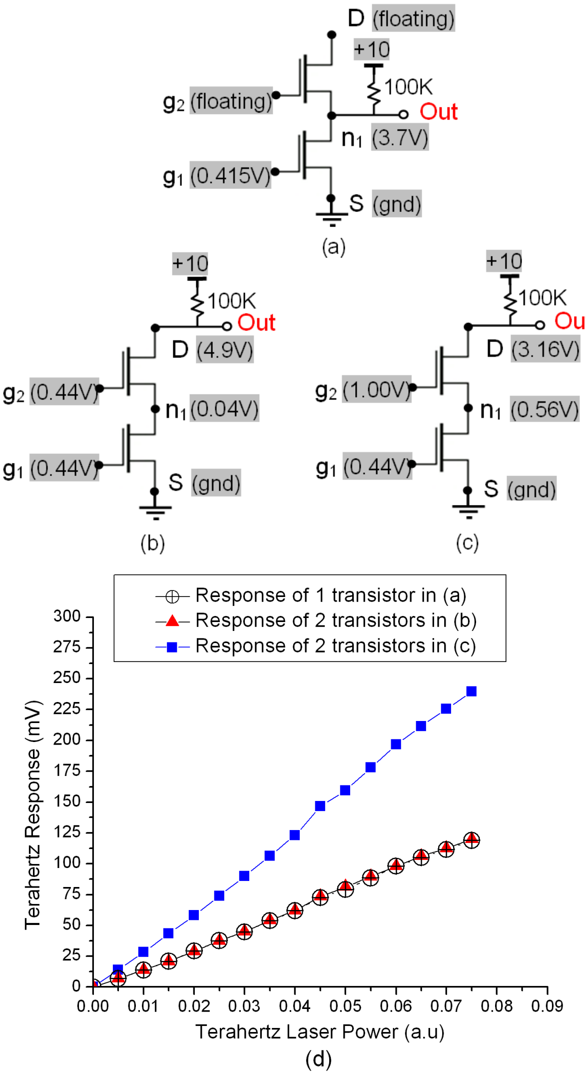

Fig. 3. Circuit schematics showing dc operating points for the three testing configurations of the two transistors test structure: (a) single transistor operated in saturation region, (b) one transistor operated in linear region and the other operated in saturation region, and (c) both transistors operatd in saturation region. The measured responsivities for the three cases are presented in (d).

According to this theory, we expect no response from symmetrical HEMT structures, when overdamped plasma waves of the same amplitude are excited at both sides of the symmetrical channel. We proved this experimentally: no response was detected without dc current flow in a symmetrical transistor (compare to [23]). The flow of dc current in this transistor creates asymmetry in boundary conditions at source and drain, asymmetry for propagation of plasma waves, and this asymmetry enhances plasma wave detection in the device [21]. In the saturation mode, asymmetry across the transistor channel increases and consequently the nonresonant THz response increases. In the linear region, the asymmetry across transistor channel is very small and in turn the transistor detects a very weak THz response. This explains the result of Fig. 3(d) in which the response from a single transistor operating in saturation region (Fig. 3(a)) is identical to the response of two transistors connected in series (Fig. 3(b)) where one is operating in linear region and the other is operating in saturation region.

Figure 4 shows the dependence of THz response on the second gate (g_2) bias voltage while keeping the first gate (g_1) bias voltage at a lower fixed value for the circuit shown in Fig. 3(b). By increasing the bias voltage of the second transistor gate, we tuned the first transistor from linear region to saturation region while keeping the second transistor operating in saturation region. Our experimental result indicates that the response increases linearly when the first transistor goes from the linear region into the saturation region. The overall response almost saturates when both transistors operate in saturation region. This result implies that the response of each transistor is independent, and the overall response of the circuit is the summation of both transistors' responses.

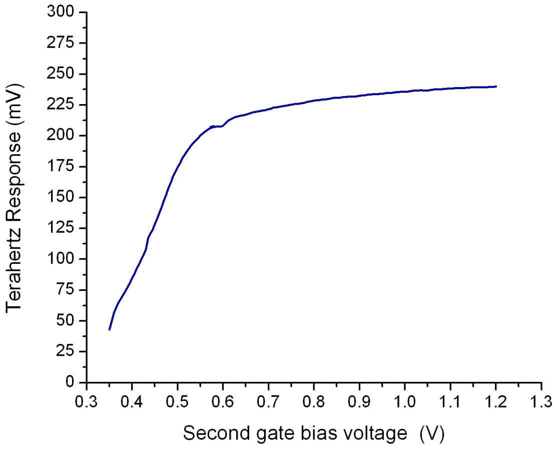

Fig. 4. The measured terahertz response versus second gate (g_2) bias voltage while the first gate (g_1) bias voltage was fixed at 0.44V for the circuit configuration shown in Fig. 3(b).

Figure 5 shows the measured THz responsivities of one transistor and up to four transistors connected in series when all of them are operating in saturation region. In order to detect the maximum responsivity from the chain of four transistors in series, we biased them with 30 V through a 100K load resistor. However, we were not able to adjust the gate-source biasing of the third and fourth transistor to be exactly similar to the other two transistors due to their loading effect. This explains our results in Fig. 5 in which the THz response of three transistors was found to be 2.92x that of one transistor, while the THz response of four transistors was found to be 4.1x that of one transistor. Still, these results show that the overall response is approximately proportional to the number of the transistors connected in series.

Since the feature size of each transistor is much smaller than the wavelength, a large number of transistors can be stacked in the focal spot of the incident THz radiation and a higher response can be detected. An even larger enhancement is expected when the dimension of the transistor chain would exceed the THz wavelength as predicted in [17,18]. Connecting many transistors in series for THz detection as described here offers another important advantage by improving the signal-to-noise ratio (SNR). SNR will be improved by a factor of square root of the number of connected transistors. This advantage makes the series connection more preferable than utilization of a simple amplifier circuit for these types of THz plasma wave detectors.

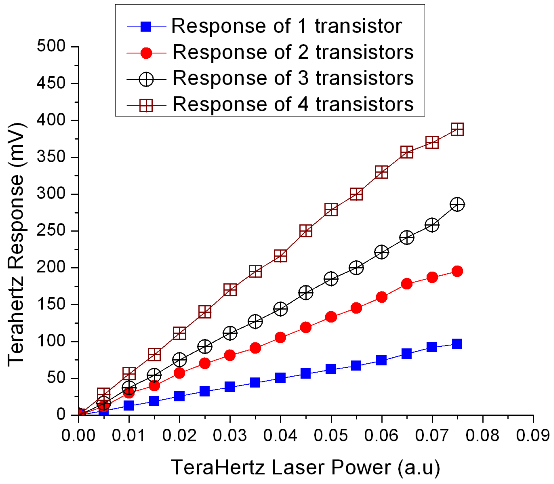

Fig. 5. Measured responsivities of one, two, three, and four transistors connected in series. All transistors were operating in saturation region.

IV. CONCLUSION

We have presented an enhanced nonresonant detection of terahertz radiation using multiple GaAs HEMTs connected in series. We proved experimentally using our fabricated symmetrical test structures of two and four transistors that the overall response of series connection is equal to the sum of THz responses of each transistor. Using such transistor chains for THz detection allows for novel circuit solution for modulation and mixing of THz response and for imaging applications.

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