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Negative Differential Resistance Devices for Generation of Terahertz Radiation

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ABSTRACT

This paper discusses the principles of operation, state of the art, and future potential of active two-terminal devices for generation of low-noise, continuous-wave terahertz radiation. These devices use transit-time, transferred-electron, and quantum-mechanical effects (or a combination of them) to create a negative differential resistance (NDR) at the frequency of interest. Many different types of NDR devices have been proposed since the earliest days of semiconductor devices and studied in detailed simulations for their power generation potential, but have yet to be demonstrated experimentally. The paper focuses on NDR devices that not only yielded significant output powers at millimeter waves frequencies and higher, but also have the strong potential of generating radiation at terahertz frequencies. Examples of such NDR devices are resonant tunneling diodes (RTDs), superlattice electronic devices (SLEDs), and InP Gunn devices. Examples of their state-of-the-art results are output powers of 0.2 mW at 443 GHz and 5 μW at 1.53 THz from InGaAs/AlAs double barrier RTDs on InP substrate; 5.0 mW at 123.3 GHz, 1.1 mW at 155.1 GHz, and 0.52 mW at 252.8 GHz from GaAs/AlAs superlattice electronic devices on GaAs substrate; and 330 μW at 412 GHz, 86 μW at 479 GHz, and 18 μW at 502 GHz from InP Gunn devices.

Keywords: Gunn devices, heterojunction, millimeter-wave devices, millimeter-wave generation, millimeter-wave oscillators, negative differential resistance, oscillator noise, phase noise, resonant-tunneling diodes, submillimeter-wave devices, submillimeter-wave generation, submillimeter-wave oscillators, superlattice, superlattice electronic device, transferred-electron effect, transit-time devices, tunneling.

This invited paper is dedicated to Prof. George I. Haddad on the occasion of his 80th birthday.

1. INTRODUCTION

The terahertz frequency range of the electromagnetic spectrum holds great promise for many systems applications, such as remote sensing, imaging, and wide-band wireless communications [1], [2]. Despite great efforts over many years, the commercial availability of solid-state sources with small size, reasonable output powers, low operating voltages, and low power consumption is still a serious obstacle for widespread systems applications in this frequency range [1], [2].

Active two-terminal devices were the first solid-state devices to be employed for power generation and amplification at microwave frequencies, and major technological challenges had to be mastered on the way from the inception of the device structures to the first experimental results in the early 1960s (see overview in Ref. [3]). Although they have been replaced mostly by three-terminal devices at microwave and lower millimeter-wave frequencies, they still hold record performance in terms of power generation capability, particularly at high millimeter- and submillimeter-wave frequencies [4]. Their most important advantage is the simple structure that does not require any compromises to be made in the device fabrication and that allows for the lowest possible series resistances in the device.

Active two terminal devices utilize various transit-time, transferred-electron, and quantum-mechanical effects (or a combination of them) to create a negative differential resistance (NDR) at the frequency of interest [3] [4]. When combined with a resonant circuit, the NDR slightly overcompensates for all the positive resistances that result from losses in the resonant circuit and any attached load, and this situation leads to sustained continuous-wave (CW) oscillations [4]. The NDR tends to decrease with the amplitude of such oscillations. This effect stabilizes the oscillations and leads to a strong suppression of AM noise in NDR oscillators.

The paper focuses on NDR devices, such as resonant tunneling diodes (RTDs), superlattice electronic devices (SLEDs), InP Gunn devices, and tunnel-injection transit-time devices. The main reason for this choice is the fact that these devices

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not only yielded significant output powers in experiments at millimeter waves frequencies and higher, but are also based on solid-state physics phenomena that provide them with a strong potential of generating radiation at terahertz frequencies. Many other NDR devices have been proposed for operation at terahertz frequencies, and their performance potential has often been explored in detailed device simulations, but power generation with these devices, in particular, at terahertz frequencies has yet to be demonstrated in experiments. Some of these devices will be mentioned in the paper where applicable.

2. RESONANT TUNNELING DIODES

Anomalous current-voltage characteristics with a broadband NDR have long been known from experience with heavily doped *p-n* junctions in Ge, GaAs, and other semiconductors. In 1958, Esaki found that interband tunneling was responsible for this phenomenon [5]. Some of the first NDR oscillators were built with such tunnel diodes, and RF power generation was even demonstrated up to millimeter-wave frequencies. In 1974, another tunneling mechanism was demonstrated experimentally, *i.e.*, resonant tunneling through a double heterobarrier [6].

Power generation with RTDs at submillimeter-wave frequencies was first demonstrated in the late 1980s, and oscillations from an InAs/AlSb RTD were reported up to 712 GHz [7]. However, the NDR in an RTD from DC upwards causes instabilities and bias oscillations at unwanted frequencies. These bias oscillations impose a severe limit on the output powers that can be extracted from resonant circuits with RTDs [4].

This limit from bias oscillations was overcome only recently, when in 2004 M. Asada and his group integrated the RTD with a stabilizing resistor made of bismuth and a slot antenna to form an oscillator emitting radiation into free space [8]. Impressive improvements in output power and maximum oscillation frequencies were subsequently reported [8]–[11]. Contrary to the first experimental demonstration of oscillations up to 712 GHz, these state-of-the-art oscillators used InGaAs/AlAs double barrier RTDs on InP substrate. Examples of their record performance are 0.2 mW at 443 GHz [9], 5 μW at 1.53 THz, and operation up to 1.55 THz [10], [11].

However, the total emitted output powers were extrapolated from measurements with a bolometer by taking into account the radiation pattern and spill-over of the hemispherical silicon lens [9], [10]. They have not been ascertained with a calibrated calorimeter such as the quasi-optical Thomas-Keating power meter [12]. In addition, the oscillation spectra were determined with a Fourier transform infrared (FTIR) spectrometer. Such FTIR spectrometers typically have a resolution limit of many GHz and the spectra of free-running RTD oscillators, for example, shown in [10] have "linewidths" of 10–25 GHz.

This is in a stark contrast to free-running oscillators with GaAs tunnel-injection transit time (TUNNETT) diodes, InP Gunn devices, and GaAs/AlAs SLEDs that all show linewidths orders of magnitude smaller than those of RTDs. These spectra were measured with commercially available spectrum analyzers, *e.g.*, from Tektronix, Agilent (= Keysight) Technologies, or Rohde & Schwarz, and some examples are discussed in the subsequent sections of this paper.

3. SUPERLATTICE ELECTRONIC DEVICES

In 1970, Esaki and Tsu proposed a unipolar device structure where Bragg reflection of miniband electrons in a semiconductor superlattice (SL) creates regions of negative differential velocity for some electric field strength in such a structure [13]. SLEDs utilize this effect to produce the NDR at the frequency of interest. SLEDs have received much attention since the 1990s [14] because the underlying Bloch effect is associated with much shorter time constants than those of the transferred-electron effect, for example, in GaAs Gunn devices [15].

GaAs/AlAs SLEDs on integral heat sinks were evaluated from wafers grown at Cambridge and at Leeds [18]. The most recent structures grown at Leeds were designed for estimated miniband widths [16] of more than 100 meV. They had 110 SL periods and each period consisted of two monolayers of GaAs for the quantum well, and 11 or 12 monolayers of AlAs for the barrier, to achieve fundamental-mode operation in D-band. SLED fabrication and packaging followed the same procedures as described in [17], [18] except for some subtle changes such as smaller nominal device diameters of 15–40 μm to facilitate much higher operating frequencies. The same type of top-hat WR-6 waveguide cavity was employed as was previously with fundamental-mode InP Gunn devices [19].

The major advantage of an oscillator circuit in a WR-6 waveguide is the availability of a calibrated waveguide test setup at D-band to confirm output powers. In addition, output powers at D-band were also ascertained with either of the two calibrated power meters PM3 and PM4 [20] [21]. These calorimetric power meters [20] [21] were also employed to measure any RF output power in waveguides above 170 GHz. Although operation in a second-harmonic mode below 190 GHz has never been observed in the more than 25 years of the cavities' use with GaAs impact ionization transit-time diodes and InP Gunn devices [4], the same procedure as in [18] was employed to verify fundamental-mode operation at D-band: These oscillators could, at constant bias for the SLED, be mechanically tuned with the back short by more than 1 GHz around their D-band frequencies. In addition, signals at the corresponding second-harmonic frequencies were extracted, and their exact frequency values in the range of 240–310 GHz were confirmed.

Examples of measured record output powers are 5.0 mW at 123.3 GHz, 2.2 mW at 134.9 GHz, 0.62 mW at 151.5 GHz, and 1.1 mW at 155.1 GHz, all in the fundamental mode, and 0.52 mW at 252.8 GHz in a second-harmonic mode. These oscillation frequencies are the highest reported to date and approximately twice as high as those observed with GaAs Gunn devices [4]. Furthermore, these oscillation frequencies exceed those of InGaAs/InAlAs SLEDs [22] and the output powers around 150 GHz are also higher than those in [22]. This superior performance confirms the strong potential of SLEDs for achieving power generation up to at least 1 THz [18].

The second-harmonic power of 0.52 mW at 252.8 GHz from a SLED on an integral heat sink is also very similar to those that were initially achieved with InP Gunn devices on diamond heat sinks [23], well-known for their superior thermal properties compared to integral heat sinks. Therefore, substantial increases in output powers from SLEDs are expected from optimized thermal management [24]. In addition, the results in a second-harmonic mode may also indicate that SLEDs are stronger harmonic generators than InP Gunn devices, which are discussed in the next section.

All SLED oscillators were also tested for their spectral purity using the Rohde & Schwartz spectrum analyzer FSU46 with suitable external harmonic mixers. Two examples, one in the fundamental mode, the other in a second-harmonic mode are shown in Figure 1.

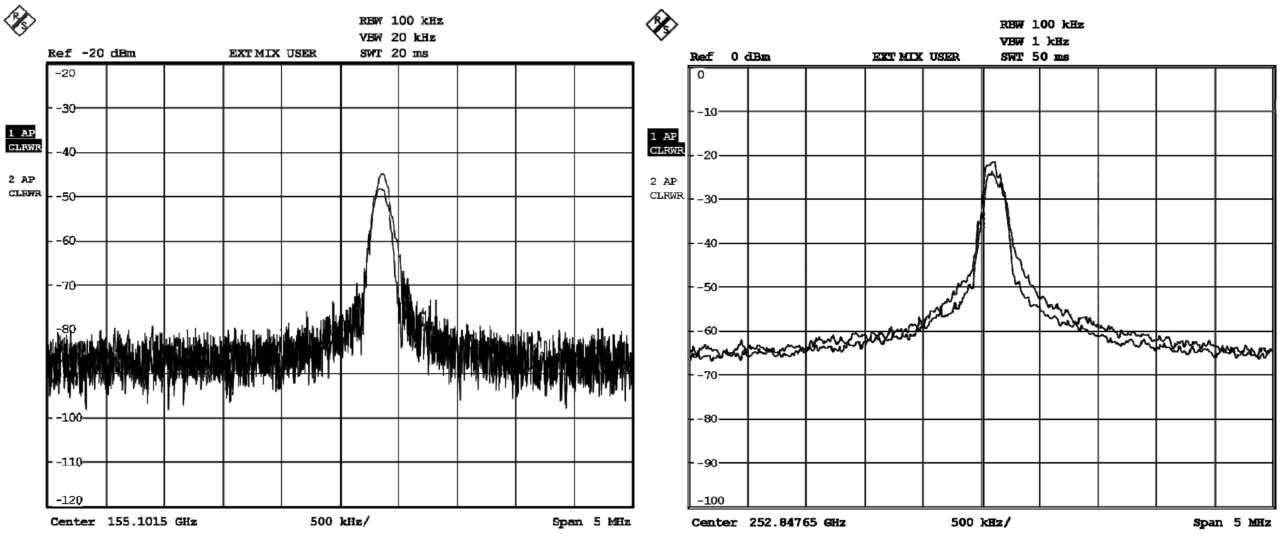

Figure 1. Spectra of free-running SLED oscillators with 1.1 mW at 155.1 GHz in the fundamental mode and 0.52 mW at 252.8 GHz in a second-harmonic mode; resolution bandwidth is 100 kHz and vertical span is 5 MHz for both spectra.

SLEDs with similar thicknesses, but higher miniband widths of the SL structures tend to oscillate at higher frequencies. Therefore, these experimental results also confirm that the average electron velocity in SLEDs increases with miniband width and they lead the way to a simple procedure to reach higher oscillation frequencies with a particular SLED design.

4. GUNN DEVICES

Gunn devices are of the only type that is discussed in this paper, but, depending on the semiconductor material system, may have relevant material parameters such as energy relaxation times that limit operation at terahertz frequencies in the fundamental mode. However, Gunn devices have long been known for their efficient operation in a second-harmonic mode [25]. Many commercially available millimeter-wave oscillators with Gunn devices utilize this second-harmonic mode, typically above 60 GHz [25]. More recently, oscillators based on three-terminal devices, such as Si CMOS or SiGe heterojunction bipolar transistors (HBT), have also exploited extraction of harmonic signals to extend the useful frequency range of a particular technology [26]–[29]. In the context of transistor oscillators, this method of harmonic power extraction is commonly referred to as "push-push" technology.

Tunnel injection transit-time (TUNNETT) diodes and Gunn devices have not only been investigated for power extraction at the second harmonic, but also at higher harmonics, in particular, at the third harmonic [24]. One example is an oscillator at 480 GHz with an InP Gunn device [24], [25]. More recent experiments show that such third-harmonic power extraction from InP Gunn devices is feasible above 500 GHz [25]. These oscillators were also tested for their spectral purity using the same Rohde & Schwartz spectrum analyzer FSU46 as before. However, the conversion loss of the aforementioned harmonic mixers increases dramatically for harmonic numbers above 20. Therefore, the Mixer/Amplifier/Multiplier Chain WR1.5MixAMC-20G from Virginia Diodes Inc. was employed [30]. Two examples, one spectrum of an oscillator with 0.06 mW at 477.9 GHz, the other one of a different oscillator with 0.018 mW at 501.6 GHz are shown in Figure 2.

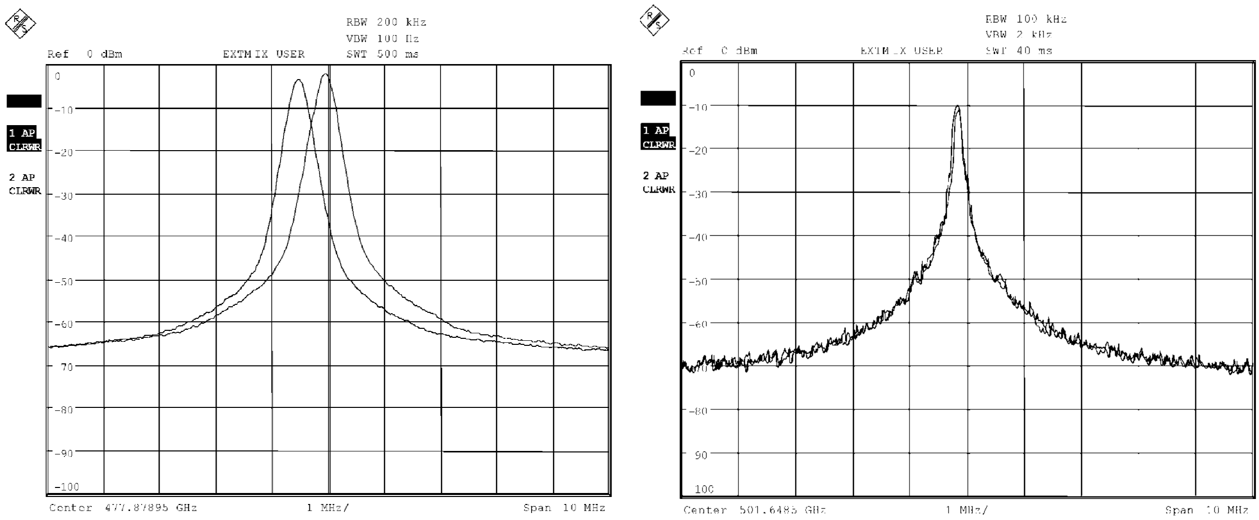

Figure 2. Spectra of free-running InP Gunn oscillators with 0.06 mW at 477.9 GHz and 0.018 mW at 501.6 GHz, both in a third-harmonic mode; resolution bandwidth is 200 kHz and 100 kHz, respectively; vertical span is 10 MHz for both spectra.

It should be noted that the spectra of Figures 1 and 2 do not show the actual linewidths of the free-running oscillators with SLEDs of InP Gunn devices, but the resolution bandwidth setting of the employed spectrum analyzer. This can be seen from the spectra of Figure 3 where a much smaller resolution bandwidth was chosen. The spectra for 0.086 mW at 477.9 GHz of Figure 2 and for 0.06 mW at 479.3 GHz of Figure 3 are from the oscillator with the same InP Gunn device, just with slightly different DC bias and back short settings.

Wide-bandgap materials such as GaN and AlGaN have been studied for their potential to yield high-power Gunn devices. Favorable material parameters, for example, are higher critical electric fields for avalanche breakdown, higher thermal conductivities, higher permissible operating temperatures, and expected higher carrier drift velocities [25]. However, high threshold electric fields and consequently higher dc bias voltages may result in severe thermal limitations of the device performance [31], [32]. Although no RF oscillations have been observed to date, bias oscillations were reported [33] and are an indication of the onset of NDR in such GaN Gunn device structures. Furthermore, major improvements in material quality or availability and in fabrication technologies are needed before devices for system applications can be developed [25].

InN is another material system suitable for Gunn devices. It offers the additional advantage of a possible graded-gap injector made from suitable group III nitride material systems. However, no experimental results have been reported to date from any InN Gunn device, and material quality or availability and suitable fabrication technologies remain major challenges [25].

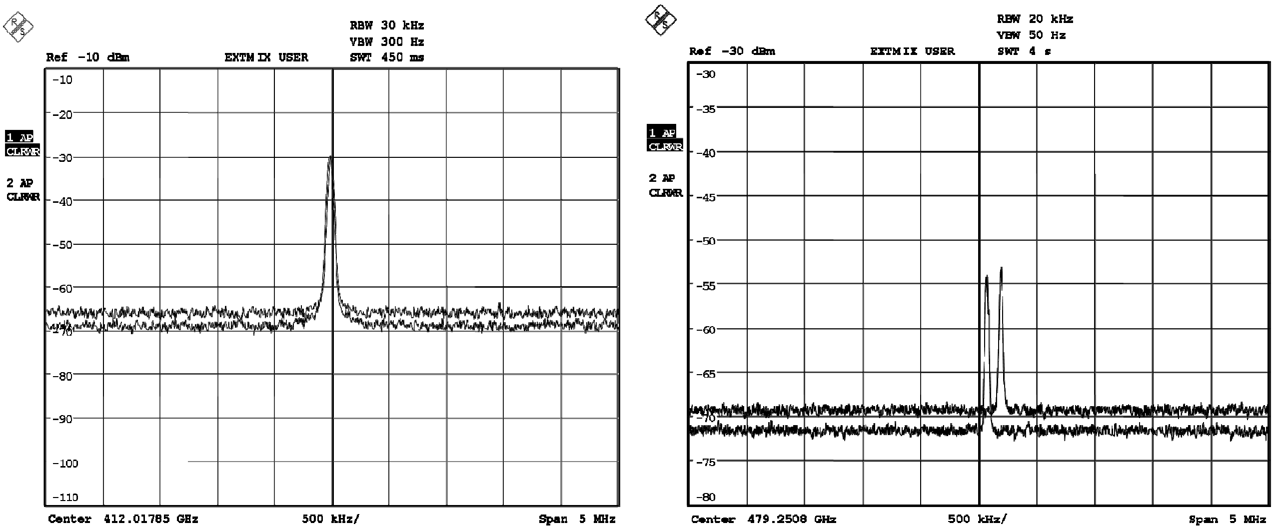

Figure 3. Spectra of free-running InP Gunn oscillators with 0.33 mW at 412.0 GHz and 0.086 mW at 479.3 GHz, both in a third-harmonic mode; resolution bandwidth is 30 kHz and 20 kHz, respectively; vertical span is 5 MHz for both spectra.

5. TRANSIT-TIME DEVICES

Among the group of transit-time diodes, TUNNETT diodes hold the greatest promise of generating significant amounts of power at terahertz frequencies. Power generation with GaAs TUNNETT diodes from 100 GHz up to 755 GHz has been reported [34], [35], but the highest output powers above 300 GHz were achieved in the aforementioned third-harmonic mode [36].

Much higher output powers at submillimeter-wave frequencies have been predicted for TUNNETT devices that utilize the unique properties of GaN/AlGaN heterojunctions [37]. Although these GaN/AlGaN TUNNETT devices do not suffer from the severe thermal limitations that were reported for the aforementioned GaN or AlGaN Gunn devices, they similarly depend on improvements in material quality and fabrication technologies before their full potential can be exploited.

6. CONCLUSIONS

The state of the art and performance potential of representative NDR devices from four different groups were discussed and, where possible, future directions were indicated. Because of their simpler structure, these NDR devices are less prone to suffering from the structure-related limitations that are known from three-terminal devices, such as the frequency limit from the base access resistance in HBTs or the up-converted noise contributions from surface states in high electron mobility transistors (HEMTs). Therefore, NDR devices are expected to play a critical role in creating commercially available terahertz sources for systems applications. Figure 4 summarizes published results from fundamental sources with NDR devices and transistors. The NDR devices in this figure are impact ionization avalanche transit-time (IMPATT) diodes, TUNNETT diodes, RTDs, and Gunn devices, whereas the transistors are HEMTs, HBTs, and Si CMOS. For a comparison, Figure 4 also includes published results from power amplifiers with such transistors.

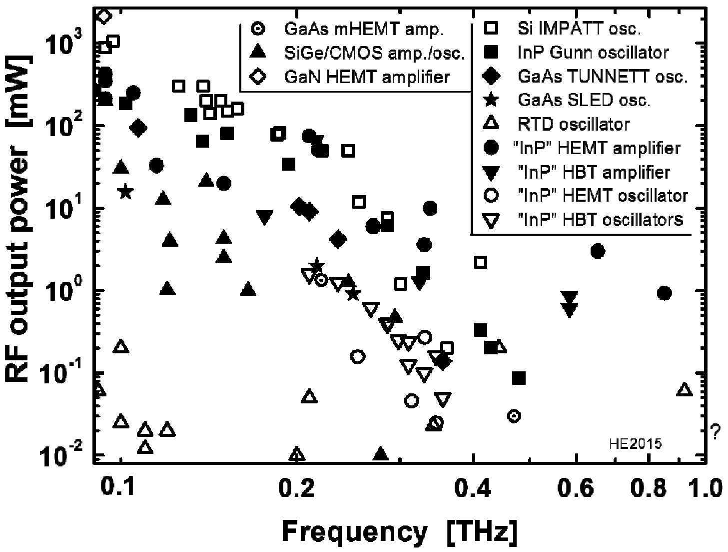

Figure 4. State of the art of fundamental solid-state sources and amplifiers with output powers above 10 µW in the frequency range 0.1–1 THz.

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