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# Microwave Detection at 110 GHz by Nanowires with Broken Symmetry

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## ABSTRACT

**By using arrays of nanowires with intentionally broken symmetry, we were able to detect microwaves up to 110 GHz at room temperature. This is, to the best of our knowledge, the highest speed that has been demonstrated in different types of novel electronic nanostructures to date. Our experiments showed a rather stable detection sensitivity over a broad frequency range from 100 MHz to 110 GHz. The novel working principle enabled the nanowires to detect microwaves efficiently without a dc bias. In principle, the need for only one high-resolution lithography step and the planar architecture allow an arbitrary number of nanowires to be made by folding a linear array as many times as required over a large area, for example, a whole wafer. Our experiment on 18 parallel nanowires showed a sensitivity of approximately 75 mV dc output/mW of nominal input power of the 110 GHz signal, even though only about 0.4% of the rf power was effectively applied to the structure because of an impedance mismatch. Because this array of nanowires operates simultaneously, low detection noise was achieved, allowing us to detect −25 dBm 110 GHz microwaves at zero bias with a standard setup.**

Exploitation of nanodevice performance in the microwave regime has been a very attractive field for researchers in recent years. Although nanodevices appear to be promising for solving problems related to device scaling, it is still not clear how they can cope with the large microwave frequency range required by current and future applications. Particular attention has been focused on novel solid-state microwave emitters and detectors for frequencies from tens of gigahertz to a few terahertz where enormous potential for application has been envisaged.[1] Furthermore, room-temperature operations must also be accomplished for practical applications, which has been a very challenging issue for novel electronic nanostructures.

One of the common problems affecting the frequency response of nanodevices is the high impedance between their terminals, which causes most of the applied microwave power, usually delivered by a 50 Ω terminated rf source, to be reflected. High impedance also causes serious vulnerability to parasitic capacitance and generally results in a long rc response time. For instance, it has been very challenging to increase the operation speed of single-electron transistors into the gigahertz range.[2] Carbon nanotubes have also been studied for applications at microwave frequencies. Li et al. showed microwave operations at 2.6 GHz from carbon nanotube transistors at a temperature of 4 K.[3] Kim et al. reported the response of nanotubes to microwave radiation in the range of 75−94 GHz.[4]

Nanostructures realized by patterning two-dimensional electron gases (2DEGs) in a compound semiconductor heterostructure have proven to be promising candidates for high-speed applications. Song et al. showed that ballistic rectifiers and nanostructured nonlinear materials, both having four terminals, could be used for microwave detection up to at least 50 GHz at room temperature.[5,6] Three-terminal ballistic junctions were also measured up to 1 GHz by Lewén et al.[7] and up to 20 GHz by Worschech et al.[8] However, these multiterminal nanostructures do not allow the fabrication of a few in parallel without interconnects, which makes it difficult to solve the high-impedance problem.

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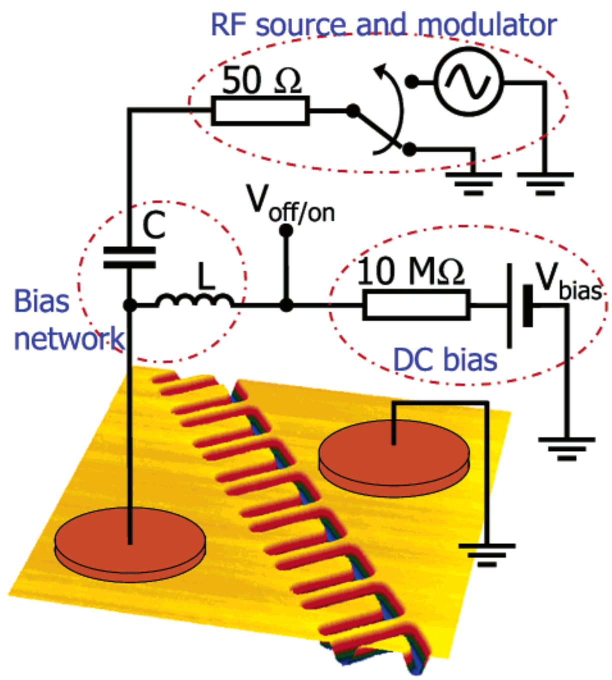


**Figure 1.** Schematic diagram of the microwave experimental setup. The bottom of the diagram is a 3D atomic-force micrograph of an array of the asymmetric nanowires, which are 1.2 $\mu$m long and approximately 100 nm wide.

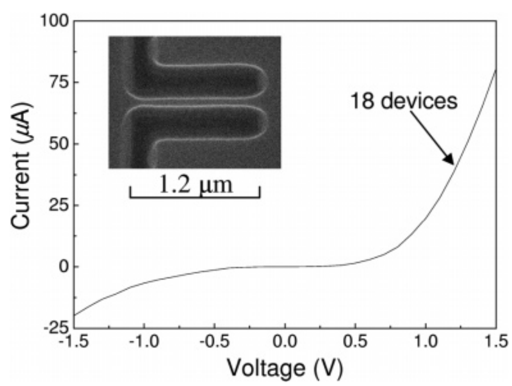


**Figure 2.** dc current−voltage characteristic of 18 nanowires connected in parallel at room temperature. The inset shows an atomic-force micrograph of a single nanowire structure, defined by the two L-shaped, etched trenches.

Recently, strong nonlinear current−voltage ($I-V$) characteristics were realized in a nanowire with intentionally broken symmetry, the so-called self-switching device. Unlike a conventional diode, however, the self-switching nanowire can be made to have a predetermined threshold voltage from virtually zero to more than 10 V by simply adjusting the nanowire width.[9] The atomic-force microscope image at the bottom of Figure 1 shows a linear array of such nanowires, connected in parallel. The layout of a single device is shown in the inset of Figure 2. It consists of two etched (and therefore insulating) trenches that tailor a 2DEG, between which a nanowire is defined. The L shape of the trenches ensures that the geometric symmetry of the nanowire is broken and also forces electrical current to flow only through the nanowire. When no voltage is applied across the wire, the nanowire is largely depleted because of the surface states on the side walls of the trenches. When a negative voltage is applied, the negative charge around the nanowire further depletes the wire itself, making it difficult for the current to flow. However, when a positive voltage is applied, the positive charges around the nanowire induce electrons into the nanowire, forming a conductive channel for the current to flow easily. This self-switching mechanism leads to diodelike behavior. Recently, a similar rectifying effect of ions in a salt solution with a concentration gradient was demonstrated in poly(ethylene terephthalate) membranes containing a single conically shaped nanopore.[10]

The self-switching nanowires are expected to operate at very high frequencies. This is due to the planar architecture of the devices, which means that the electrical contacts are laterally separated rather than placed on the surface and the back side (substrate). This leads to substantially lower parasitic capacitance between contacts than in a conventional vertical device of the same size. Furthermore, the new working mechanism does not rely on any minority carrier diffusion, and no barrier structure is used along the current direction at all. Without being limited by the above factors that normally determine the speed of conventional semiconductor diodes, the asymmetric nanowire is expected to function at very high frequencies. Recently, operations of the nanowire structures in the terahertz range have been envisaged in Monte Carlo simulations.[11]

Devices designed for microwave applications normally have a 50 Ω impedance so that all or most of the applied rf power is truly delivered to the device rather than being reflected back. Like most nanostructures, a single self-switching nanowire has a very high impedance, typically on the order of megaohms. What differentiates the asymmetric nanowire from other novel nanodevices, such as the ballistic rectifier or the three-terminal ballistic junction, is that the two-terminal nature makes it straightforward to integrate many in parallel and form an array, without the need for any extra lithography step to make interconnects. It is possible to design not only a linear array where all of the nanowires lie along a single line but also far more complicated structures. For example, the bottom image in Figure 1 shows how U-shaped trenches (each made of two L-shaped trenches) define a number of asymmetric nanowires in parallel. Furthermore, it is easy to fold such a linear array as many times as required. In this way, a large area, even an entire wafer, could be turned into an active material. Unlikely classic diodes, the planar structure also allows direct coupling to free-space radiation, with a perpendicular incidence onto the array. Such a feature can be useful to exploit new applications in a wider frequency range (e.g., for terahertz detection).

In our work, two different high-frequency mesa designs were adopted. The active region in mesa A is 7 $\mu$m wide, typically allowing five to six nanowires to be fabricated in parallel. Mesa B is 45 $\mu$m wide in the middle and can accommodate many more nanowires in one column to realize a lower (better matched) impedance. Similar results were obtained in all structures that were measured in the microwave experiments. Only results from a mesa B structure with

18 nanowires will be reported here. All of the measurements were carried out at room temperature in darkness.

The nanowires were fabricated from a modulation-doped InP/InGaAs/InP quantum well wafer, grown by metal-organic vapor-phase epitaxy (MOVPE). The 2DEG in the quantum well was 41 nm below the surface. The carrier density and mobility at temperature $T = 4.2$ K are $1.0 \times 10^{16}$ m$^{-2}$ and 45 m$^2$/V s, respectively. The ohmic contacts were formed by annealing Au/Ge/Au metal layers at 390 °C. Both single nanowires and nanowire arrays were defined by electron-beam lithography followed by HBr-based wet etching of the L- or U-shaped trenches. The simple planar architecture of the nanowire allowed us to fabricate an array of many elements in a single high-resolution lithography step without the need for interconnection layers, as shown in the atomic-force microscope picture in Figure 1.

We fabricated and tested a number of arrays with different numbers of elements and layouts. Nanowires were 1.2 $\mu$m long and 60−100 nm wide. As showed in ref 9, the threshold voltage of the device is strongly dependent on the channel width. To achieve microwave detection without a dc bias requires the current−voltage characteristic to be nonlinear around zero bias. This was done by carefully choosing the channel width to have the threshold as low as possible, meaning that the channel was slightly wider than previously reported. For this reason, a small amount of reverse current can be seen in the current−voltage graph in Figure 2. We also managed to tune the actual channel widths by selectively etching the InGaAs quantum well of wide (about 100 nm) nanowires until a desired $I-V$ characteristic was reached.

The experimental setup shown in Figure 1 is the standard setup for the characterization of microwave diode detectors. The microwave signal from 100 MHz to 110 GHz was generated by an Agilent 8510XF and applied via 150 $\mu$m coplanar probes in the ground−signal−ground configuration. The array was biased by a dc bias network (modeled as an LC network) embedded in the Agilent 8510XF and a digital voltage supply connected in series with a 10 MΩ resistor. The dc voltage across the array was measured with an HP4678B digital voltmeter. The microwave was fed to the device via a modulator, which switched the rf single on and off. When a microwave signal was applied to the array, the voltage across it changed. The output voltage was therefore a rectangular wave, which could be monitored conveniently with an oscilloscope. The detection output voltage, $V_{out}$, measures the magnitude of the rectangular wave, which is the difference between the voltages across the array when the microwave signal is switched on and off. This enabled us to get rid of the influence of the thermal drift and any offset voltage due to light and temperature effects of the device and the dc meters. The 10 MΩ resistor is much larger than the sample resistance at relevant biases to this experiment. The dc voltage drop over the resistor gives a good measure of the dc bias current. With the bias network, we can measure the device performance at the optimum dc bias current so that the nanowires can provide the strongest nonlinearity for microwave detection.

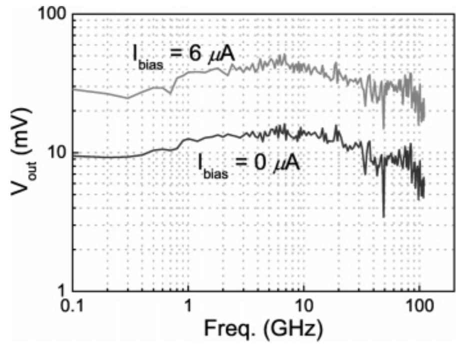


**Figure 3.** Frequency response of the nanowires from 100 MHz to 110 GHz at zero bias and 6 $\mu$A, measured at room temperature.

The whole setup was controlled by a PC, allowing automatic measurements of the dc $I-V$ characteristic, rf frequency, and power dependences. To determine how much nominal rf power was actually delivered to the nanowires, we measured the power loss due to cables, connectors, and probes. At the highest frequencies, the total loss was as high as 3.5 dBm. These losses at different frequencies were compensated for by the computer, which adjusted the rf power at each frequency point.

Figure 3 shows the detected output voltage $V_{out}$ as function of frequency. The first trace was measured with a bias current of $I_{bias} = 6$ $\mu$A, and the second was measured without any bias applied. The power was kept constant at about 280 $\mu$W in the measurements. As can be seen, both traces show the same features in the frequency dependence. We believe that these features were due to the measurement setup and the substrate layout (i.e., mesa and metallizations) rather than the actual device or noise. Furthermore, the impedance of our arrays was still far from being the standard 50 Ω, causing most of the applied rf power to be reflected and most likely inducing resonant features at some particular frequencies.

The experiments showed that the nanowires had a stable frequency response as the frequency increased by 3 orders of magnitude from 100 MHz to 110 GHz (the highest frequency of our setup). This is, to the best of our knowledge, the highest frequency performance that has been demonstrated to date in various types of novel electronic nanodevices. The results are in agreement with the findings of the recent Monte Carlo simulations by Mateos et al., who envisaged operations in the terahertz range.[11] Terahertz measurements and design optimizations of the asymmetric nanowires, which are beyond the scope of this letter, are particularly interesting for the asymmetric nanowires because the planar device structure allows the detection of free radiation coming from the normal direction of the device surface, which is not possible for a normal detection diode.

The microwave detection sensitivity of an electronic nonlinear device is determined by the nonlinearity in its current−voltage characteristic. Figure 4 shows the detected output voltage $V_{out}$ as a function of the dc bias current $I_{bias}$ at 110 GHz. The microwave power was fixed at 280 $\mu$W, the highest power that we could reach at 110 GHz with our equipment. If the small-signal approximation is assumed,

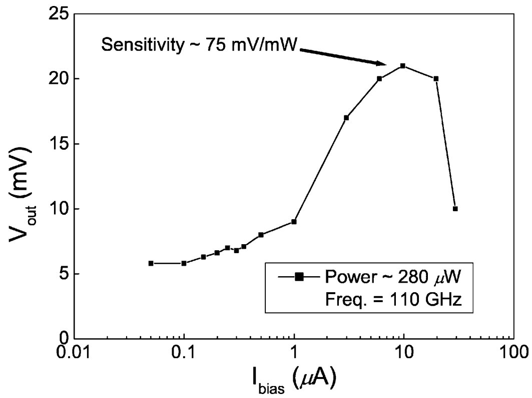


**Figure 4.** Detection output voltage of the asymmetric nanowires $V_{out}$ as a function of the applied dc bias current $I_{bias}$. The frequency of the applied microwave was fixed at 110 GHz, and the power was fixed at 280 $\mu$W.

then the detection sensitivity of a nonlinear device is given by

$$\frac{G'_d}{4G_d}$$

where

$$G_d = \left.\frac{dI}{dV}\right|_{V=V_0}$$

is the dynamic conductance and

$$G'_d = \left.\frac{d^2I}{dV^2}\right|_{V=V_0}$$

is the second derivative of $I(V)$ at a dc bias of $V = V_0$.[12] At zero and low dc bias current values, the $I-V$ trace in Figure 2 was almost linear, and a sensitivity of about 20 mV of dc output/mW of nominal input of the 110 GHz signal was reached. As the dc bias current increased to about 10 $\mu$A, where the $I-V$ characteristic showed the strongest nonlinearity, we were able to reach a sensitivity of 75 mV/mW. The 110 GHz result in Figure 4 is in very good agreement with the expected performance calculated from the dc characteristic in Figure 2. Furthermore, the dc impedance of the 18 parallel nanowires at $I_{bias} = 10$ $\mu$A is about 50 K$\Omega$, meaning that only about 0.4% of the nominal input rf power was effectively applied to the structure, with the rest reflected. This implies a great potential for optimization.

The rf power dependence of the device was also studied at a number of frequencies. Unless the applied power was very high, we found that the device output followed the so-called square law; that is, the output voltage is proportional to the square of the input voltage and therefore is proportional to the input power. This is shown in Figure 5, where the device was measured at 110 GHz and at zero dc bias. A linear dependence, shown by the fitting (dashed line), was well maintained as the microwave power spanned over 2 orders of magnitude. It also shows that the small-signal approximation previously assumed was correct, ensuring that we could relate the sensitivity directly to the ratio of the second derivative of the $I-V$ curve to the first derivative. The square-law property is desirable for many microwave applications (e.g., as a demodulator). Furthermore, because an array of nanowires operated simultaneously, the overall signal-to-noise ratio was expected to be lower than in a single nanowire. Indeed, we were able to detect a $-25$ dBm microwave at 110 GHz at zero bias using only the standard unoptimized setup shown in Figure 1. There is much room for even greater detection sensitivity to be realized by the optimization of the $I-V$ characteristic and by using an array with many more asymmetric nanowires. Unprecedented performance can also be anticipated if nanowires made by bottom-up growth techniques, by which great controllability of structures and compositions has been achieved in recent years, are to be used.[13−18]

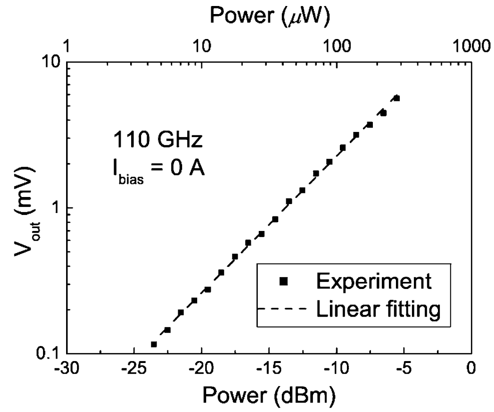


**Figure 5.** Detection output voltage of the nanowires versus the power of the 110 GHz signal (in dBm). The dashed line is a linear fit showing a very good square-law dependence.

In summary, we have demonstrated microwave detection with novel asymmetric nanowires up to 110 GHz. Both stable frequency response and low noise, zero-bias detections were realized. We have also discussed other advantages, including the detection of radiation coming from the normal direction of the structure and a square-law response as well as potentials for terahertz applications. Future exploitations may also be in the area of telecommunications because the nanowires are both very light-sensitive and electrically very fast.

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