

# **A New Technology for Terahertz Electronics**

*Thin-Film Devices Based on Metal-Insulator Tunnel Junctions*

**Based on a whitepaper for Phiar Corporation – 13 August 2003**

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# **A NEW TECHNOLOGY FOR TERAHERTZ ELECTRONICS**

## **Executive Summary**

The terahertz region (nominally 0.1-10 THz) separates electronics from photonics, and has historically been difficult to access. Semiconductor electronics run out of steam after ~100 GHz due to transport time limitations. Photonic devices falter below ~10 THz because the photon energy drops to the thermal energy. Phiar has developed a new technology that extends the range of electronics into the terahertz. It does not use semiconductors; instead, it is based on metal-insulator tunneling structures to form diodes for detectors and ultra-high-speed tunneling transistors for oscillator-based transmitters. With these devices, Phiar has designed detectors and transistors for operation in the terahertz region. Phiar's patented double-insulator structures produce high performance because of greatly enhanced nonlinearity.

Besides being extremely fast, Phiar devices are made entirely of thin film materials – metals and insulators – and so may be fabricated on top of CMOS circuitry or on a wide-variety of substrate materials, such as plastic or glass. The result is complete integrability, and consequently, low cost. In addition, devices may be fabricated onto large-area flat panels or flexible sheets, enabling completely integrated microwave/millimeter-wave/submillimeter-wave sensor and emitter arrays. These devices operate at low voltage allowing compatibility with CMOS circuitry. Coupled with innovations in antenna design and traveling wave devices, Phiar technology makes terahertz electronics a reality.

Phiar's terahertz technology opens up practical applications in high-speed data interconnects, terahertz imaging, and highly-integrated radar and communications systems. The gap between electronics and photonics has closed.

# A NEW TECHNOLOGY FOR TERAHERTZ ELECTRONICS

## Introduction

The largely untapped frequency region between 100 GHz and 10 THz (the “terahertz” region) holds promise for a wide range of commercial and military applications. Midway between the microwave and infrared spectral regions, terahertz frequencies have been historically difficult to access.

At the high frequency end, infrared optoelectronics cannot operate significantly below 10 THz. Since these devices employ photon-electron particle interactions, as photon energy  $h\nu$  decreases below thermal energy  $kT$  the device ceases to operate efficiently unless it is cooled, which adds significant cost and weight.

At the low frequency end, semiconductor electronic devices cannot operate at frequencies significantly above 100 GHz. Transport time across the semiconductor junction is limited by drift and diffusion speeds. For example, a charge traversing a 0.1  $\mu\text{m}$ -wide junction with saturation velocity 10<sup>7</sup> cm/sec would take  $\tau_t=1$  ps to cross, which would yield a cutoff frequency of  $f=1/2\pi\tau_t=160$  GHz.

Phiar Corporation has patented a technology which bridges the terahertz gap. It doesn't need epitaxy or high temperature. It's extremely fast, thin film, and low cost. And it opens new possibilities for terahertz applications.

Based on metal-insulator tunnel junctions, Phiar's technology extends the range of electronics beyond the 100 GHz barrier to 10 THz. In these devices, charge transport through the junction occurs via electron tunneling, which has a time constant of  $\sim 10^{-15}$  seconds. Charge transport to and from the junction occurs via plasma oscillation in metals, which is easily supported with low loss in the terahertz range of interest. Furthermore, epitaxial

growth and high process temperatures are not required. Thus, integration of terahertz electronics onto low-loss insulating substrates (e.g. —glass, sapphire, ceramic, plastic) or onto silicon integrated circuits is possible. Phiar is employing this concept in practical components – detectors, transistors, mixers and other devices – to provide a full suite of ultra-fast integrated components for building high-frequency electromagnetic wave circuits and systems. This leap in performance and flexibility enables a host of new applications for terahertz electronics.

This whitepaper describes Phiar's metal-insulator technology, starting with the basic building block: Phiar's patented MIIM tunneling diode, a very fast, very efficient new diode structure. Then the operation of a new transistor is described, the MIIMIM hot electron tunneling transistor, which is a new twist on an old transistor concept. Finally, the implications that this technology has on a number of commercial applications are discussed.

## MIIM Tunneling Diode

Infrared and millimeter-wave detectors based on rectifying metal-insulator-metal (MIM) tunnel-junction diodes have been investigated since the 1960s,<sup>i</sup> but these basic devices have suffered from low efficiency and poor device stability. For a diode rectifier to operate efficiently, it must have a sufficiently nonlinear current-voltage characteristic (sharp turn-on). And for a rectifier to operate at high frequencies, it must have high “on” state conductivity. Unfortunately, in the simple MIM diode one encounters a trade-off between nonlinearity and conductivity – a MIM diode can have one or the other but not both. The current-voltage curves in Figure 1 illustrate this phenomenon.

Phiar's earliest invention was a superior diode using two insulators instead of one to produce MIIM (metal-insulator-insulator-metal) diodes.<sup>ii</sup> In the MIIM diode, high conductivity and high nonlinearity may be obtained simultaneously, resulting in an efficient detector capable of operating with carrier frequencies well above 10 THz. In fact, early work at Phiar focused on developing optical detectors and modulators for 1.55  $\mu\text{m}$  (193 THz) telecommunications applications.

### Theory of Operation

As seen in Figure 2, adding a second insulator layer dramatically increases diode nonlinearity. The insets in the top graph show energy band diagrams of the MIIM diode in forward and reverse bias. The diode consists of a low barrier insulator and a high barrier insulator. In forward bias, a triangular quantum well forms between the two insulators. When the lowest quantum well energy level falls below the Fermi level of the first metal, electrons readily tunnel through the device using the quantum level as a pathway. In reverse bias, no quantum well forms and electrons must tunnel through both barriers without the aid of an intermediate pathway. The result is a very nonlinear and highly asymmetric I(V) curve – much more semiconductor diode-like than the simple MIM device. The top graph of Figure 2 shows theoretical I(V) curves while the bottom graph shows measured I(V) curves from an experimental MIIM device.

### Fabrication

A critical step in the formation of MIIM devices is growth of very thin, uniform, and high density tunnel junction insulators. Currently these films are sputter deposited; however, Phiar plans to eventually use atomic layer deposition (ALD), which enables controlled, layer-by-layer growth of very thin oxides. ALD oxides have high film density (e.g.  $\text{ZrO}_2$ )<sup>iii</sup> and excellent stoichiometry (e.g.  $\text{Nb}_2\text{O}_5$  and  $\text{Ta}_2\text{O}_5$ ).<sup>iv</sup> The expected consequence is better control over device properties and improved device reliability.

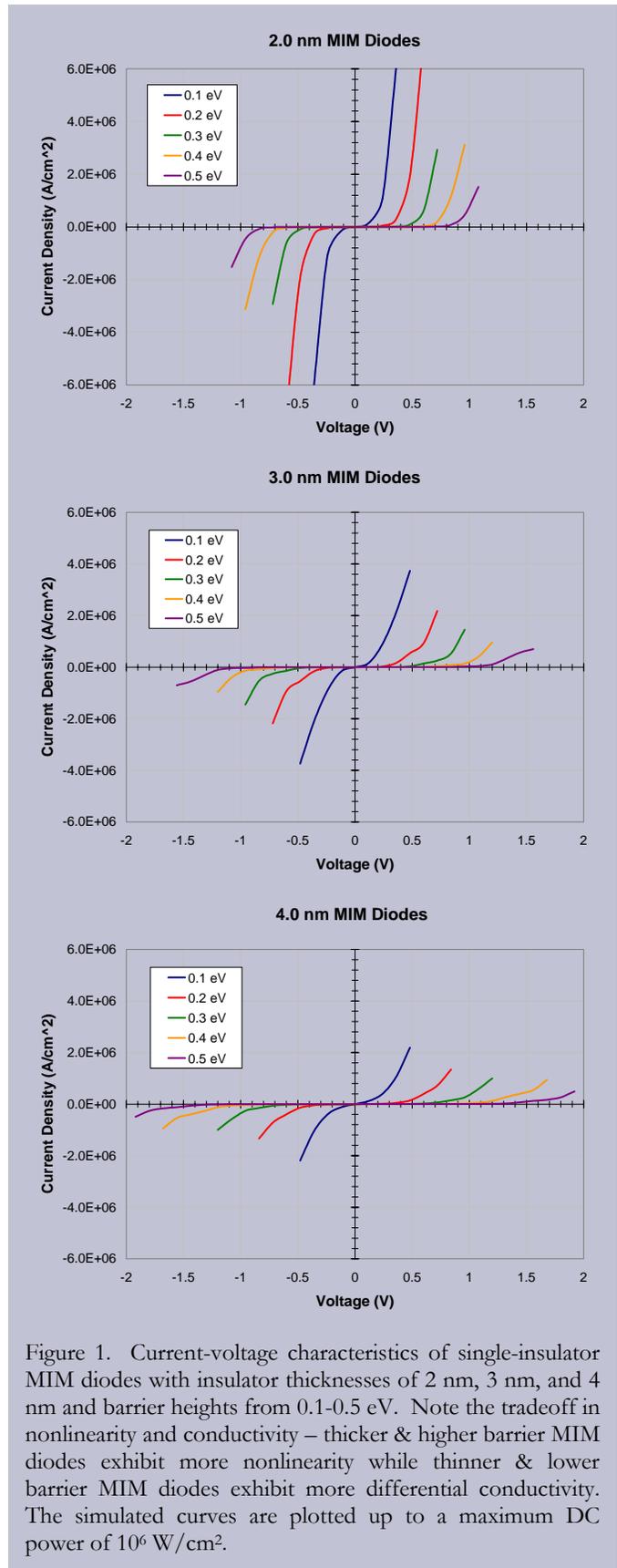


Figure 1. Current-voltage characteristics of single-insulator MIM diodes with insulator thicknesses of 2 nm, 3 nm, and 4 nm and barrier heights from 0.1-0.5 eV. Note the tradeoff in nonlinearity and conductivity – thicker & higher barrier MIM diodes exhibit more nonlinearity while thinner & lower barrier MIM diodes exhibit more differential conductivity. The simulated curves are plotted up to a maximum DC power of  $10^6 \text{ W/cm}^2$ .

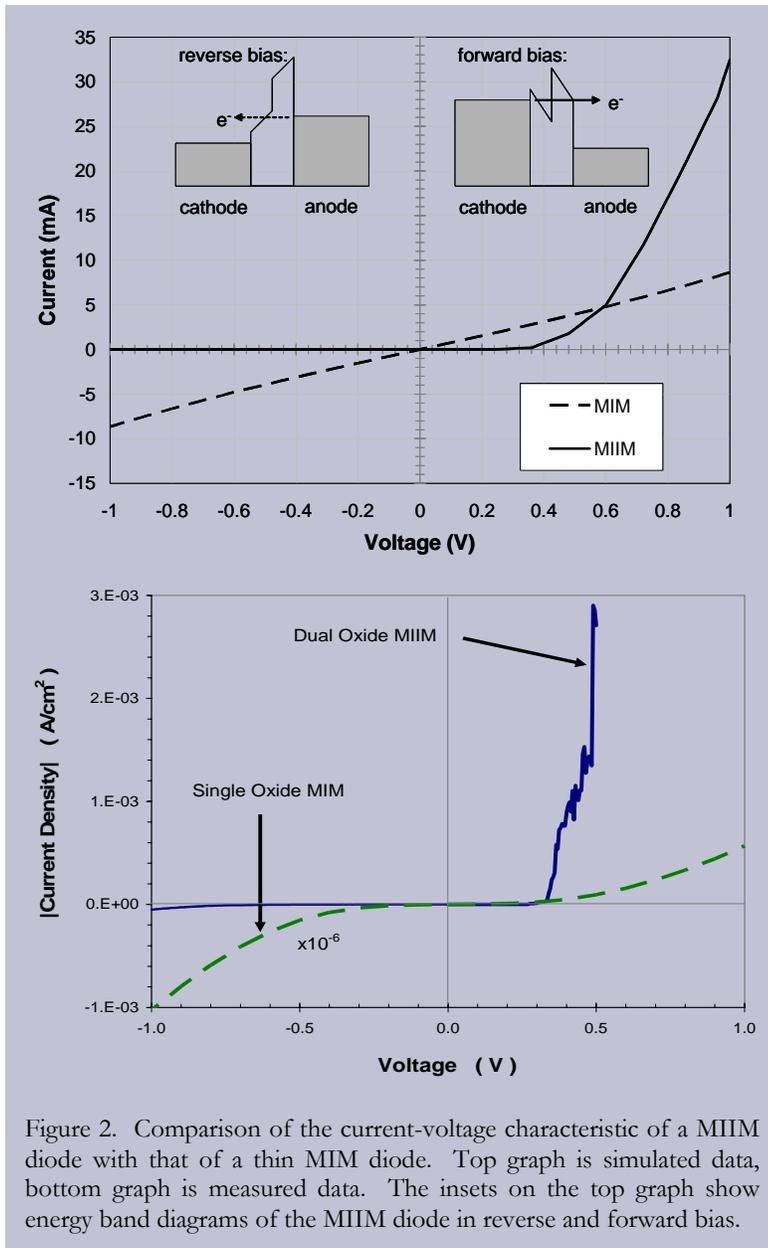


Figure 2. Comparison of the current-voltage characteristic of a MIIM diode with that of a thin MIM diode. Top graph is simulated data, bottom graph is measured data. The insets on the top graph show energy band diagrams of the MIIM diode in reverse and forward bias.

## Terahertz Detectors

The basic Optenna™ detector is a tiny antenna connected to a metal/double-insulator/metal (MIIM) diode (see Figure 3). The antenna is sized on the order of a wavelength, roughly a millimeter for terahertz radiation and one micron for near-infrared wavelengths. The two poles of the antenna overlap to form the MIIM sandwich. This MIIM region is a nonlinear diode – the “crystal” in a crystal radio.

The antenna picks up the incident terahertz waves just as a radio antenna picks up radio-frequency waves, except that the frequency is much higher. The MIIM diode at the focus of the antenna rectifies the signal.

### Detector Performance

Optenna™ detectors operating in the terahertz frequency range exhibit excellent detectivity and sensitivity. At 3 THz, simulated NEP  $\sim 1 \times 10^{-13}$  W/Hz<sup>1/2</sup>, and  $D^* \sim 9 \times 10^{10}$  cm Hz<sup>1/2</sup>/W ( $T=300$ K,  $V_{\text{bias}} = 0$ ,  $R \sim 2.3$  A/W), values which are nearly the same as the sensitivity of much slower superconducting microbolometers at  $T=4$  K. More expensive and fragile GaAs Schottky barrier diodes, both whisker contact and planar, are the primary competing technology for high-speed detection (rectification & mixing) at terahertz frequencies.

As the comparison in Table 1 shows, Optenna detectors have superior noise figure, and comparable speed and responsivity to Schottky detectors. Note that while the best Schottky diodes have higher cutoff frequency than the Optenna detector, the response of Schottky diodes falls off much more quickly with frequency than do MIM and MIIM diodes due to the GaAs plasma frequency. The primary advantage of the Optenna detector, though, is that it is a much more practical technology due to its monolithic, integrable nature.

Optenna detectors offer:

- Ultra-high speed  $\rightarrow$  beyond 10 THz
- Thin-film structure  $\rightarrow$  deposited on silicon and other surfaces
- Low voltage  $\rightarrow$  <1 volt, compatible with CMOS levels
- Wide operating temperature range, including above 100°C
- Manufacturability: no exotic materials or processes, low deposition temperatures

- Reliability: Thin insulators similar to those used in Optenna devices deposited by atomic layer deposition exhibit greater lifetimes and durability than equivalent thermally grown SiO<sub>2</sub>.

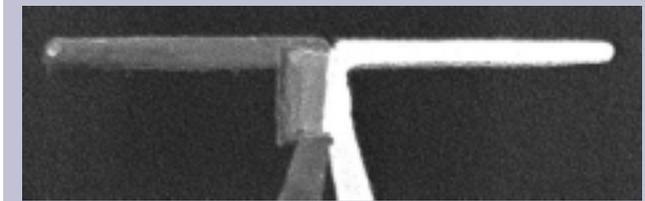


Figure 3. SEM micrograph of Optenna detector. Horizontal arms are dipoles and rectangular section is MIM tunnel junction stack.

### Antenna Innovations

Along with innovations in metal-insulator diodes, Phiar has patents in antenna designs and matching networks. These proprietary innovations are backed by significant capabilities in electromagnetic modeling and simulation. The antenna innovations are directed in particular at improving ultra-high-frequency antenna operation.

### Traveling Wave Detectors

When the diode is connected to an antenna, the antenna impedance has an effect on frequency response. Because of this, detection of very high frequencies requires that the diode be very small to

reduce capacitance. In some cases, the size required to achieve this low of capacitance is beyond the limits of state-of-the-art fabrication equipment. To circumvent the RC-time limit, Phiar has patent-pending traveling wave detector structures.<sup>v</sup>

In a traveling wave device, electromagnetic energy couples from the antenna to an anti-symmetric surface plasmon mode of the MIIM tunnel junction. This mode of propagation, commonly called the slow-mode surface plasmon,<sup>vi</sup> couples strongly to

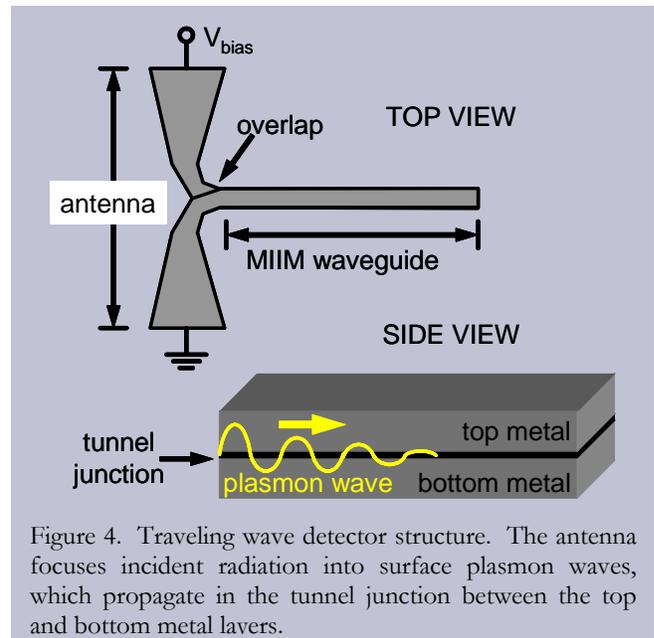


Figure 4. Traveling wave detector structure. The antenna focuses incident radiation into surface plasmon waves, which propagate in the tunnel junction between the top and bottom metal layers.

Table 1. Comparison of high-speed mixer/rectifier diodes.

	MIM Detector	MIIM Optenna Detector	Whisker-contact GaAs Schottky	Planar membrane GaAs Schottky
Junction area	1 x 10 <sup>-10</sup> cm <sup>2</sup>	1 x 10 <sup>-10</sup> cm <sup>2</sup>	5 x 10 <sup>-10</sup> cm <sup>2</sup>	N/A
Cutoff frequency	3 THz	9 THz	25 THz	13 THz
Junction capacitance	0.4 fF	0.18 fF	0.25 fF	2 fF
Differential resistance	130 Ω	100 Ω	25 Ω	6 Ω
Ideality factor	>7	~1.5	1.51	1.5
Noise current	20 pA/Hz <sup>1/2</sup>	0.25 pA/Hz <sup>1/2</sup>	30 pA/Hz <sup>1/2</sup>	N/A
Peak Responsivity	~0.5 A/W	9 A/W	8 A/W	N/A

tunneling electrons, resulting in efficient rectification, even at very high frequencies. Figure 4 illustrates the general structure of a traveling wave detector.

## MIIMIM Hot Electron Tunneling Transistor

The MIMIM hot electron tunneling transistor (a.k.a. MOMOM or tunneling hot electron transfer amplifier, THETA) was first proposed by Mead in 1960.<sup>vii</sup> Figure 5a shows the basic MIMIM structure and Figure 5b shows Phiar's patented enhancement, the MIIMIM transistor.<sup>viii</sup> The emitter-base insulator layer is an MIIM tunnel junction, designed to inject hot electrons across the base metal and collector junction. The middle metal base region is thin enough that hot electrons injected from the emitter junction flow through the base without significant scattering. In this way, current injected into the base controls current from emitter to collector, thereby providing current gain.

Several aspects of the hot electron transistor make it attractive for terahertz applications:

- Fast charge transport → high cutoff frequency
- High base conductivity → high maximum oscillation frequency
- Low voltage operation → integration with CMOS circuitry
- Thin-film device → compatible with variety of substrates & IC technologies

One might ask: why resurrect a forty year-old device? There are a number of practical difficulties with the device:

- Oxide pinholes and metal microbridges
- Oxide defects and traps
- Metal-oxide interface states
- Base metal pinholes
- Base metal mean free path

The answer is that a number of things have changed in the forty years since Mead first introduced the MIMIM – particularly advancements in materials, fabrication, and numerical modeling. Phiar has created innovations and developed expertise in areas that make the hot electron transistor a viable technology:

- MIIM diode emitter → increases current gain and frequency response
- Proprietary designs for increasing the frequency response
- Proprietary processes to improve performance, yield, and reliability
- Atomic layer deposition → improves control over device properties
- Numerical simulation → increases understanding of device performance

### ***Predicted Performance***

Phiar has created analytical as well as full, numerical quantum-mechanical models of MIIMIM transistor performance. This section describes the operation of the MIIMIM hot electron transistor and the performance predicted by these models.

Table 2 gives results of modeled high-frequency performance of MIIMIM transistors. One can see from the values in the table that these transistors have potentially very high performance up to terahertz frequencies. RF output power and power efficiency have been computed assuming a basic class A

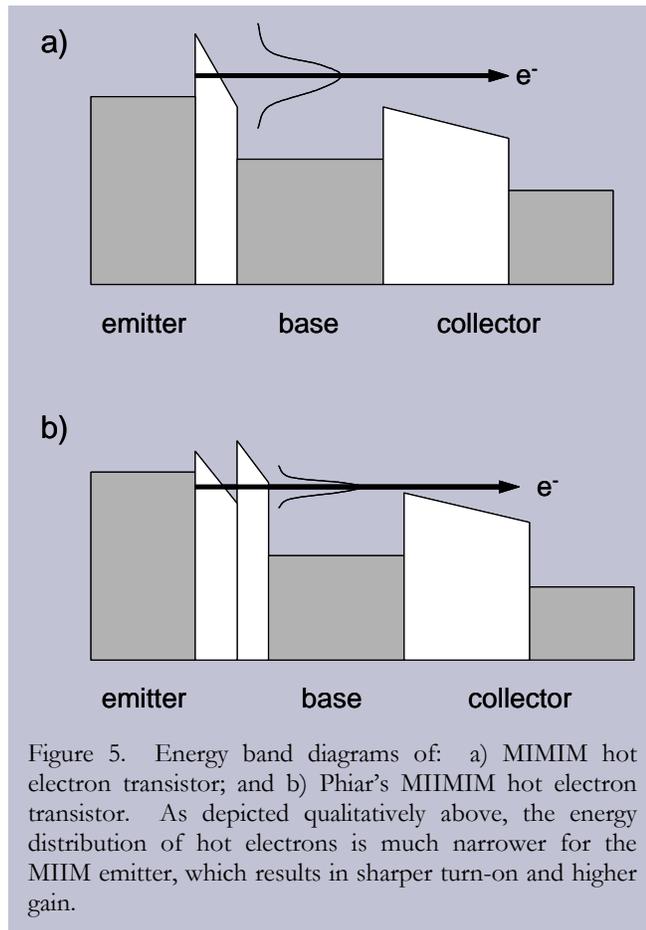


Figure 5. Energy band diagrams of: a) MIMIM hot electron transistor; and b) Phiar's MIIMIM hot electron transistor. As depicted qualitatively above, the energy distribution of hot electrons is much narrower for the MIIM emitter, which results in sharper turn-on and higher gain.

Table 2. Small signal performance parameters of a MIIMIM transistor.

Parameter	MIIMIM
Transconductance, $g_m$	66 S/mm
Cutoff frequency, $f_T$	1.7 THz
Max oscillation frequency, $f_{max}$	3.8 THz
Unilateral power gain, U, $f=300$ GHz	19.6 dB
RF output power, $P_{RF}$	250 mW/mm
Power efficiency, $P_{RF}/P_{DC}$ , $f=300$ GHz	35%

amplifier configuration. Other amplifier types may yield higher powers and efficiencies.

From Table 2 one may see that the MIIMIM transistor has high predicted performance. Compared with other transistor technologies, the MIIMIM is fast. As Table 3 shows, the frequency response of the MIIMIM is several times that of the best III-V transistors.<sup>ix</sup>

### Terahertz Sources

One of the main reasons that terahertz applications have not fully materialized yet is the lack of a small, low-cost, moderate-power terahertz source.<sup>x</sup> The root causes of this problem have already been described in the introduction. Using the MIIMIM transistor in an oscillator configuration, an integrated terahertz source becomes possible. According to Phiar's modeling, the transistor may be made to oscillate at frequencies above 1 THz.

### Applications

Phiar's technology enables a wide range of new applications for terahertz and even lower frequencies. The following discussion outlines some examples of enabled applications.

#### Terahertz Interconnects

As microprocessor technology advances, increasingly it is the speed of communications among interconnected devices in a system rather than the

Table 3. Comparison of high-frequency transistor technologies.

Transistor	$f_T$ (GHz)	$f_{max}$ (GHz)
MIIMIM	1700	3800
Si CMOS	150	30
Si bipolar	50	73
SiGe HBT	270	260
SiGe MODFET	62	116
GaAs MESFET	160	133
III-V HBT	305	800
III-V HEMT	362	740

speed of the microprocessor that limits the system performance. Electrical interconnects are approaching their limits, particularly in high performance applications. They are sufficiently fast only over very short distances, and require increasing power levels and signal reconditioning over longer circuit board distances. Optical interconnects have been researched for two decades but have yet to reach commercial application. Major impediments include the expensive packaging associated with optical feedthroughs and the cost of optical fiber alignment, in addition to the cost of hybrid semiconductor components. A technology that is successful in the market is one that provides not just high performance but also low cost. Electrical interconnects are a low cost solution, but increasingly do not provide adequate performance. Optical interconnects provide high performance, but at currently unacceptable costs. Phiar's terahertz-wave technology provides a very low cost-to-performance ratio, making it a compelling solution for a growing number of applications.

Terahertz-wave interconnects provide the high-data-rate advantages of optics with the easy interconnectivity of radio waves:

- Advantages of terahertz-wave frequencies

- Sufficiently high bit rates to carry at least 10 Gb/s
- Sufficiently low frequency waves to penetrate chip packages
- Large collection area for ease of alignment
- Efficient generation and detection of terahertz waves using Phiar components
- Circumventing need for expensive high-frequency RF circuit boards
- Easy alignment: Optical fiber interconnects require precision alignment, which is expensive and precludes use in applications where units are aligned only by mechanical guides. In comparison terahertz wave transmitters and detectors require alignment with much coarser millimeter precision.
- No optical feedthroughs: Optical links require expensive packages with optical feedthroughs. Terahertz waves penetrate standard chip packages, allowing the use of standard packages. For example, clock signals can be broadcast to an chip or set of chips through their packages.
- No wires: Compared to electrical interconnects, terahertz-waves provide higher signal frequencies. For free-space terahertz-wave links, there is no physical connection between devices, so that inserting additional units is simple. Where needed terahertz waves can enable zero-insertion-force connectors.

Terahertz waves have not been a serious contender for interconnects until recently because of difficulty in producing terahertz-wave signals. Phiar device technology allows using these waves for interconnects, providing ease-of-use and cost advantages like those of electrical interconnects, and the performance advantages of optical interconnects. The market for such a dramatically superior and enabling technology is huge, starting with clock distribution and high-end processing and routing applications and leading to a broad array of mainstream microprocessor applications.

Phiar's anticipated products in this market will be terahertz transceiver chips and licensed device technology for integration onto microprocessors, memory chip, etc.

### ***Terahertz Imaging***

Access to terahertz wave generation and detection opens up opportunities for imaging

applications in the medical, security, and manufacturing fields. Like lower frequency radio waves, terahertz waves are able to penetrate many materials, allowing evaluation of what's inside. And like higher frequency optical waves, terahertz waves have short enough wavelength to allow adequate imaging resolution.

With the ability to provide both terahertz illumination sources and terahertz detector arrays, Phiar would provide the key components for this emerging market.

In the medical arena, terahertz imaging offers many of the advantages of x-ray imaging but without harmful, high-energy radiation. Additionally, these images could be recorded in real-time using electronic image sensors, eliminating the need to process x-ray film and allowing real-time evaluation of the patient. Examples of medical imaging applications include dental imaging of teeth and screening for cancerous cells in tissue samples.

Security applications of terahertz imaging systems include the screening of luggage and people for weapons, explosives, and contraband.

In the manufacturing environment, terahertz imaging may be used for quality control inspection of manufactured parts, such as wire-bonding of electronic circuits in plastic packages.

### ***RF-on-Flex***

Many radio frequency sensors, such as automobile collision avoidance systems, unmanned aerial vehicle (UAV) radars, and portable communications systems, require microwave or millimeter-wave antenna arrays integrated with high-speed electronics. Current fabrication techniques for these systems involve assembling a large number of separate antenna/transceiver modules together to form the antenna array. This approach is expensive due to the cost of assembling these components together and due to the cost of the individual modules, which generally require III-V electronic circuits.

Phiar's high-speed, thin-film technology solves this problem by allowing the direct integration of antenna arrays and high-speed electronics onto large-area, flexible substrates. Thus, an entire radar transceiver may be fabricated onto a single piece of plastic, which in-turn may be glued conformally onto an automobile bumper or an aircraft skin. Likewise,

low-cost millimeter-wave communications transceivers could be attached to windows or the sides of buildings to enable high-bandwidth, wireless networking in urban areas. Furthermore, these systems could incorporate electronically steerable arrays. Roll-to-roll and large panel manufacturing, such as that used in thin-film displays, would enable fabrication of these systems on a large scale.

### ***Low-Cost, High-Speed Electronics***

The cost of conventional GaAs- and InP-based high-speed electronics is in part limited by substrate size. A 6-inch GaAs wafer, for instance, holds less than one quarter the number of die as a 12-inch Si wafer. At roughly the same cost to process each wafer, that gives Si the edge in cost – except that the silicon circuit may not be able to perform the same high-speed function as the GaAs circuit.

Using Phiar technology, the same high-speed circuit could be fabricated on 12-inch silicon wafers or even on large plastic or ceramic panels. That means lower manufacturing cost for microwave and millimeter-wave circuits, which in-turn means new applications and new markets for these systems.

### **Conclusion**

Phiar terahertz sources and detectors have the advantages of:

- Ultra-high speed → frequency response > 1 THz
- High performance → comparable with that of III-V Schottky diodes and high-speed transistors
- Thin film fabrication → freedom to choose suitable substrates, large-area fabrication
- Innovative antenna designs → higher efficiency and better signal & carrier separation

These characteristics in-turn enable a wide range of applications:

- High-speed interconnects
- Terahertz imaging
- RF-on-flex

Coupled with other thin film components – MIM capacitors, metal inductors, and thin film resistors – Phiar’s metal-insulator devices form the core of a new terahertz electronics technology, helping bridge the terahertz gap between optics and electronics.

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