Progress in producing terahertz detector arrays

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Fabricated with semiconductor-manufacturing tools, room-temperature terahertz-range detector arrays would enable faster, lower-cost, and less intrusive security screening.

A ‘terahertz camera,’ capable of detecting electromagnetic radiation at frequencies between 300GHz and 3THz, would enable production of real-time, noncontact images of objects concealed behind dielectric materials, including clothing, packages, envelopes, paper, and plastic wraps. With a sufficiently high resolution for direct object identification (see Figure 1), such a device would trigger development of innovative security systems with a double advantage of increased effectiveness and higher throughput over visual/manual inspection. But so far, no practical, mainstream technology has emerged to generate, handle, and detect terahertz radiation.

The first route toward the terahertz camera was paved by radio astronomers, who employed cryogenically cooled superconducting electronics to image the cosmic-background radiation. Such systems have excellent performance, but they are low-volume applications manufactured at very high cost.

Micrometric-textured materials, such as paper, plastics, and clothing, are opaque to visible and IR light because of light scattering rather than absorption. The transparency of these materials to terahertz radiation derives from its wavelength (0.1–1.0mm). The terahertz wavefront passes through small obstacles without significant deviations, just like sound waves can freely travel through a cornfield or water waves can propagate through a cane thicket. For the same reason, terahertz radiation can travel much further than IR light through aerosols made of micrometric particles like dust, smoke, or fog. With these capabilities in mind, a second route to terahertz imaging adapts existing thermal imagers—long-wave IR cameras—by changing their pixel size and optics. However, blackbody emission from room-temperature objects rapidly drops for wavelengths longer than 10μm, making passive terahertz imaging difficult. In addition, active thermal sensors discard both phase and spectroscopic information about the radiation they detect.

We believe that a third route to achieving a practical terahertz camera may be emerging from technologies employed in micro-electronics manufacturing. The cutoff frequency of nanoscale transistors recently passed 300GHz, thus entering the realm of terahertz integrated circuits. Micro-electronics technology with materials commonly employed by the high-frequency semiconductor industry allows for mass production and room-temperature operation. Solid-state terahertz cameras are developed as either hybrid designs or monolithic circuits, where detectors are constructed simultaneously in the same process alongside the readout circuit. The monolithic approach ensures

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high accuracy in pixel positioning and deterministic control of parasitic losses. Integrated antennas are then used to couple the radiation to the nanoscale diode or transistor (see Figure 2). In addition, monolithic arrays are compatible with integrated single-pixel amplifiers, input-matching networks, and switches for readout.

Terahertz-radiation detection by nonlinear effects well beyond cutoff frequency has been demonstrated in CMOS and type-III–V field-effect transistors with deep-submicron channels. \(^3\) A 600GHz focal-plane array has been realized by Wuppertal University and Innovations for High-Performance Microelectronics GmbH in Germany based on 0.25\(\mu\)m CMOS technology. \(^4\) In each pixel, a silicon negative-channel metal-oxide semiconductor transistor with a cutoff frequency of 35GHz (acting as detector) is coupled with a patch antenna and a 16MHz low-noise amplifier. The detection principle is based on the nonlinearity of the device response, which survives well beyond cutoff: the 600GHz signal is coupled to both gate and drain terminals and mixing takes place in the channel. CMOS technology represents an interesting candidate for future low-cost, portable, low-consumption, and integrated terahertz cameras.

However, high electron-mobility transistors and diodes based on type-III–V semiconductors—gallium arsenide (GaAs), indium arsenide, indium phosphide, gallium nitride (GaN)—display higher cutoff, lower noise, and higher power density than CMOS at high microwave frequencies. An ultrawide output bandwidth of 10GHz or more for each pixel enables phase-sensitive detection, spectral encoding, radar ranging (a kind of 3D standoff imaging), and high-speed wireless communications. By extending such microwave systems to the terahertz range, they would be granted the high directionality and lateral resolution typical of optical systems, as already demonstrated with a single-pixel 590GHz radar developed by NASA at the Jet Propulsion Laboratory. \(^5\)

Our group is fabricating monolithic arrays of transistors and diodes based on GaAs and GaN, used as terahertz-radiation detectors. \(^6\) To increase the cutoff toward terahertz frequencies, parasitic capacitances need to be minimized. To this end, we use air-bridge technology and mesa isolation extensively. Moreover, submicron gate and diode junctions are of Schottky type (metal-on-semiconductor) and display a ‘T’ section—see Figure 3(b)—obtained by tri-layer electron-beam lithography. This allows for both low junction capacitance and low series resistance. The junction resistance can be further decreased by applying DC bias—see Figure 3(a)—to reach higher detection frequencies. A typical ‘T’-gate device with a 0.2\(\times\)2.0\(\mu\)m\(^2\) area can detect radiation up to 1THz. Other components are needed for a full terahertz electronic-imaging system such as generators, optics, and waveguides, but the monolithic detector array is

Figure 2. Scanning-electron-microscope image of an air-bridge submicron Schottky diode, showing a gold anode contact—suspended between two 5\(\mu\)m-high mesas—that ends in a nanoscale Schottky junction to the gallium arsenide epitaxial layer. (bottom inset) The junction is surrounded by the ohmic contact. The anode and cathode are shaped into the arms of a 270GHz dipole antenna. (top inset) Photograph of a monolithic array of such Schottky diode detectors.

Figure 3. Maximum detectable frequency, \(f_{\text{det max}}\), at room temperature for the Schottky diode rectifier with T-section anode shown in (b). The junction area (0.2\(\times\)2.0\(\mu\)m\(^2\)) is the ‘foot’ of the ‘T’. i: Current. \(V_{\text{bias}}\): Bias voltage.

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definitely an important step toward high-performance terahertz imaging technology.

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