Filling the THz gap with new applications

The electromagnetic spectral range 0.1–100THz has many scientific uses for investigating the fundamental excitations in matter, but now new imaging opportunities are coming into view for medical and security applications that could launch terahertz technology into the public domain. Semiconductor technology is key to many of these developments, explains Dr Mike Cooke.

The electromagnetic spectrum, until recently, has been divided into two broad areas: radio/microwave and light/optics. Radio and microwave frequencies have been accessed directly with electronics (up to about 100GHz), while long-wavelength infrared radiation and beyond (say from 10THz) depends on 'photonics', the production of photons through quantum transitions (1THz corresponds to a photon energy of 4.1meV). In between is what is often called the 'terahertz gap', although the far infrared (FIR) covers some of the same territory.

But photonics and electronics have been steadily narrowing this gap in the electromagnetic spectrum (see Figure 1). On the electronics side, indium phosphide/indium gallium arsenide heterojunction bipolar transistors (HBTs) have reached a unity gain cut-off (f_T) of at least 845GHz at 220K (745GHz at room temperature) using a pseudomorphic (lattice-mismatched) grading of the base (12.5nm thick) and collector regions [1] (see facing page). The device (pictured opposite) has been scaled both vertically (reducing electron travel distance) and laterally (increasing speed of charge and discharge of the HBT). The lattice mismatch introduces a strain gradient, thereby enhancing electron velocities, giving further reductions in current density and charging times. The group that made the device, under Milton Feng at the University of Illinois at Urbana-Champaign, is no doubt working to improve this as I write. Among its aims, this group definitely has in its sights a 1THz transistor for faster computers, more flexible and secure wireless communications systems, and more effective combat systems.

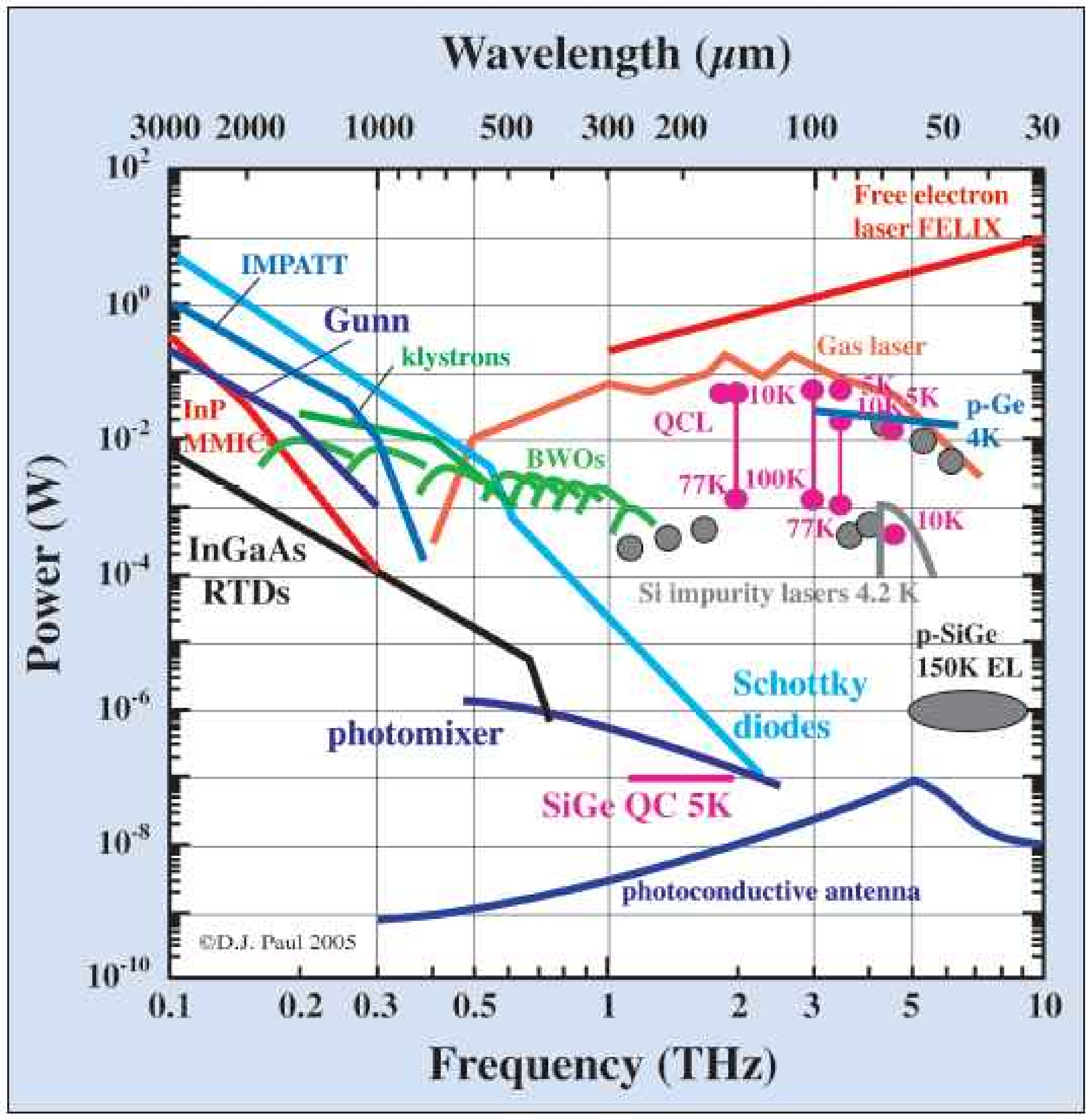

Figure 1: Graph showing output powers from THz sources in the literature up to June 2005 (from www.sp.phy.cam.ac.uk/~SiGe/THz.html), with thanks to Dr Douglas J Paul, senior researcher at the University of Cambridge, UK. Paul reports that the only major change since 2005 is that there are a few new GaAs QCL results at frequencies down to 1.7THz at low temperatures [e.g. Walther et al, App. Phys. Lett. vol. 89, p231121, 2006]. Magnetic-field-confined QCLs have pushed below 1.5THz [12].

Silicon germanium HBTs have also been produced at IBM and tested at Georgia Institute of Technology [2], with an f_T of 510GHz at 4.5K (352GHz at room temperature). These new gain devices are in addition to the two-terminal non-gain diodes (e.g. tunnel, resonant tunnelling, IMPATT, Gunn/TED, Schottky) developed and used at these frequencies for a number of years.

However, here we will focus on techniques that are optoelectronic in nature. The wavelength range from 1mm to 100μm (300GHz–3THz) corresponds to an approximate photon energy between 1.24–12.4meV or to an equivalent black-body temperature (E/k) in the range 14–140K, which is well below the ambient background on Earth (300K~26meV). Some authors extend the THz range to 100GHz–10THz.

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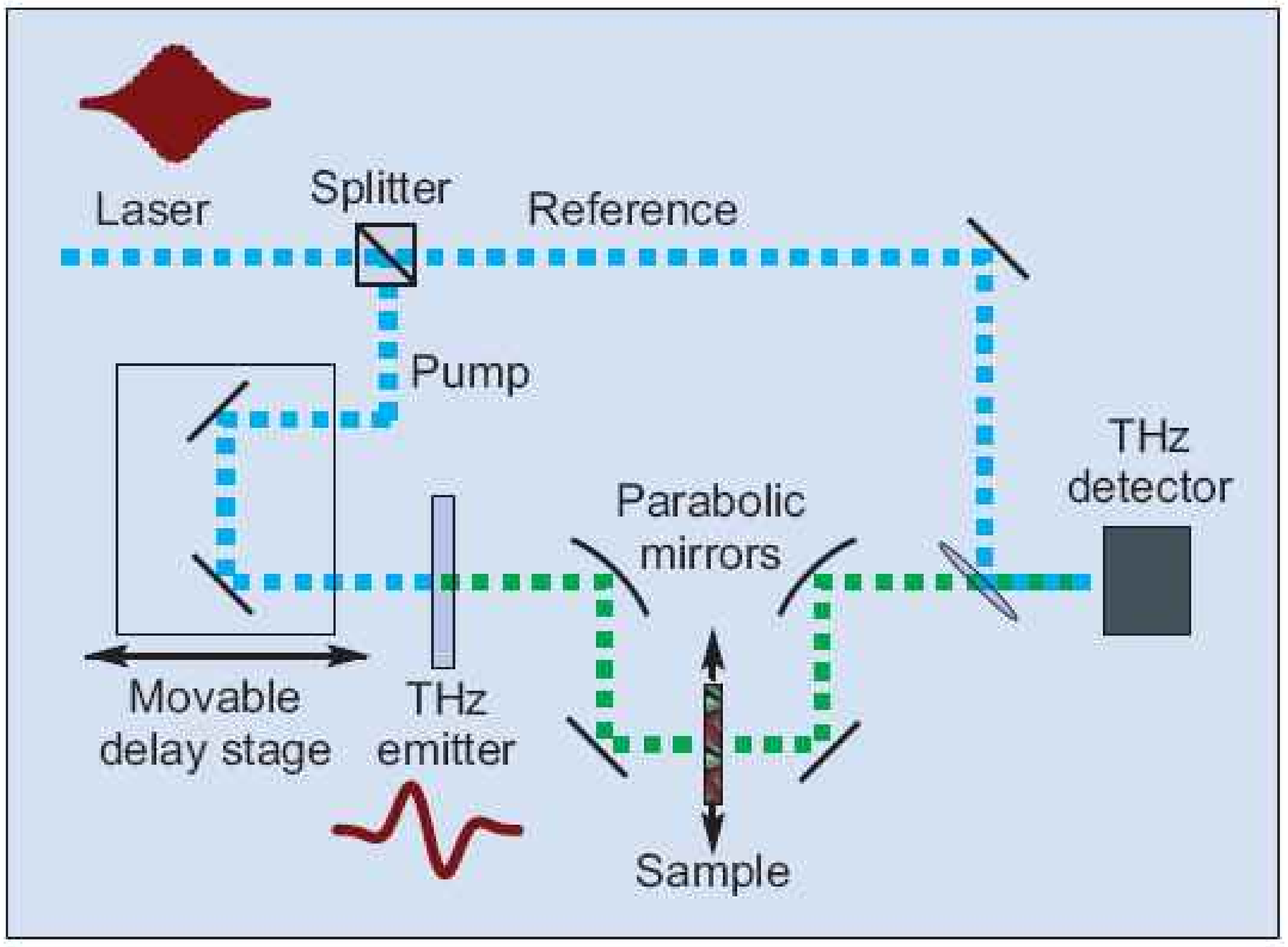

Figure 2: Typical time-domain spectroscopy system.

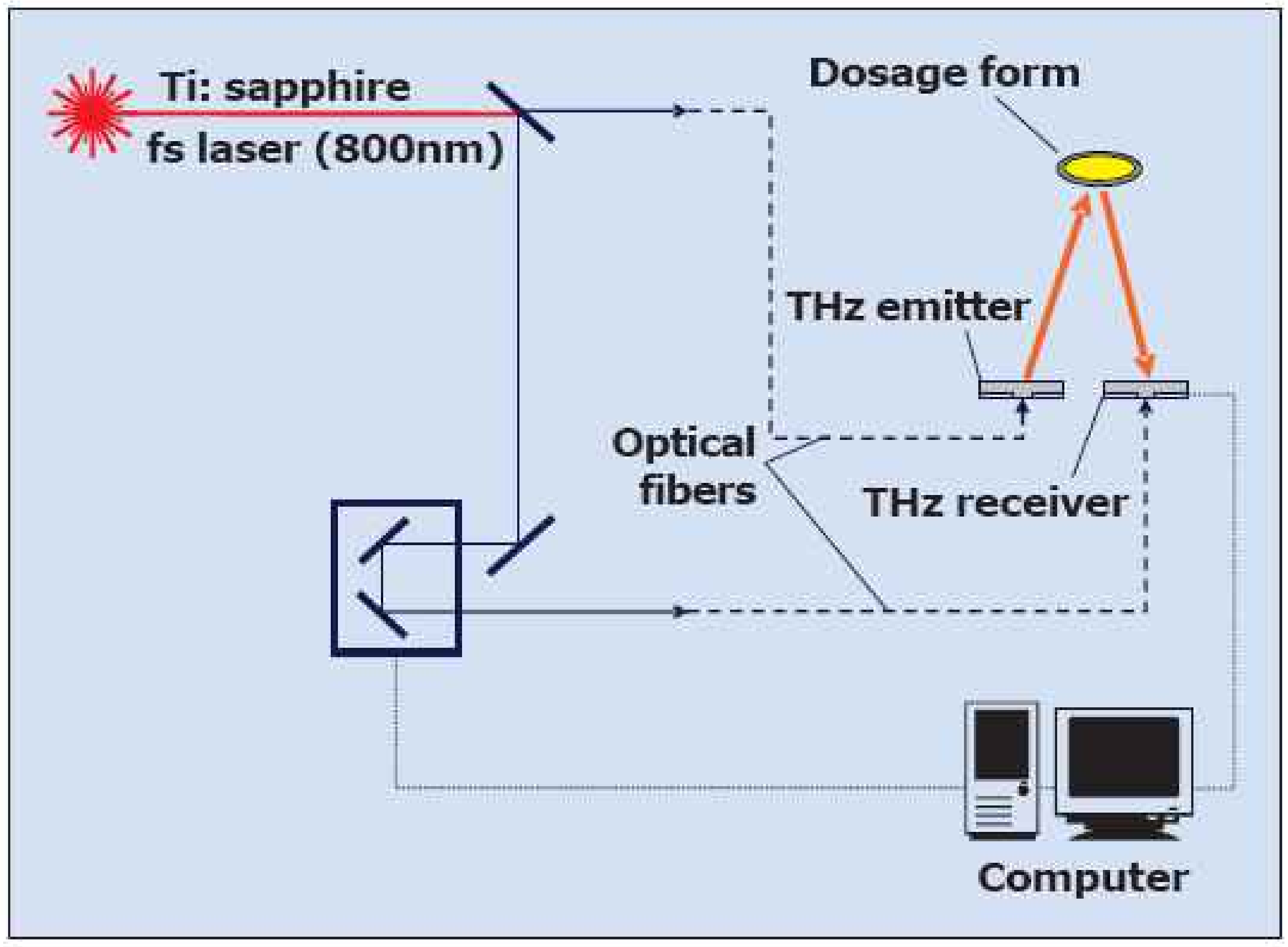

Figure 3: A pulsed imaging configuration.

Imaging drive

T-ray imaging has been a major driver of recent interest in THz technology. Since T-rays can penetrate most materials except water and metal, such imaging provides opportunities in a number of areas such as the medical arena, where organic material can be penetrated without the damage of ionizing radiation (e.g. x-rays), albeit with a lower spatial resolution from the much longer wavelengths involved. The security industry is also interested in systems that can peek inside clothing for metal weapons without harm to the general public.

Unlike visible and infrared light, where often only intensity information is available, THz spectroscopy can measure the amplitude and phase of the electric field on a timescale that is shorter than the duration of a single oscillation. Time-domain spectroscopy (TDS) looks for system responses to pulsed signals that contain only a few cycles and hence are broadband in terms of frequency. From these studies, one can improve the understanding of condensed-matter and molecular-matter states (vibrations, charge density oscillations, excitons, superconducting gaps, spin waves, protein folding, etc) or enhance molecular recognition. But TDS can also be used to create T-ray imaging systems (Figure 2). Imaging technology that analyses the TDS response of objects moving in a focused beam was pioneered by Nuss and others at Bell Laboratories in the mid-1990s [3]. These systems operate close-in to the object.

T-ray focusing can be made reflectively or with lenses constructed from silicon, high-density polyethylene or a material called Picarin. Silicon has the advantages of low adsorption and chromatic aberration throughout the THz range, but a high refractive index (~3.42) leads to reflection losses at the air–glass interface (Fresnel losses). A technique for overcoming the latter problem is to use an anti-reflective coating (ARC). Polyethylene has less reflection loss, but a small amount of absorption above 1THz and a resonance at 2.2THz. Picarin is another plastic material for THz lenses with a refractive index of 1.56 and small losses in the THz range.

Toshiba-owned TeraView (a spin-off of Toshiba Research Europe, Cambridge, UK) has developed THz techniques to detect cancerous cells using molecular markers, such as water, to provide spectral and absorption information to differentiate between cancerous and non-cancerous tissues, non-invasively. The aim is to greatly improve on conventional biopsy techniques and associated surgery by more precisely identifying areas to be excised, reducing the number of procedures and enabling earlier, more accurate diagnosis. The company also promotes THz technology (imaging and spectroscopy) for drug discovery and formulation, security screening/detection and material characterization (including electronic component analysis). TeraView uses measurements of transmitted or reflected terahertz radiation giving spectral, time-of-flight and direct signal strength to provide images (Figures 3 and 4). From the raw data, one can make inferences on refractive indices, amplitude and phase changes, and sample thickness (Figure 5).

Frequency domain

A more traditional THz application is spectroscopy. One such application has been the extension of radio astronomy to shorter wavelengths. NASA's Cosmic Background Explorer (COBE) indicated that approximately half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the sub-millimeter and far-IR regions (600GHz–7.5THz) [4]. Interstellar and intergalactic spaces contain large quantities of singly ionized nitrogen, H_2D^+, carbon monoxide, and many other species that have THz emission lines.

Geophysicists are also interested in many of the same gases in the earth's atmosphere and these can be accessed by satellite observations of water, oxygen, chlorine and nitrogen compounds, etc. THz emission lines from the Earth's stratosphere and upper troposphere give information on ozone destruction, global

Figure 4: TeraView's Imaga 2000 THz imaging platform.

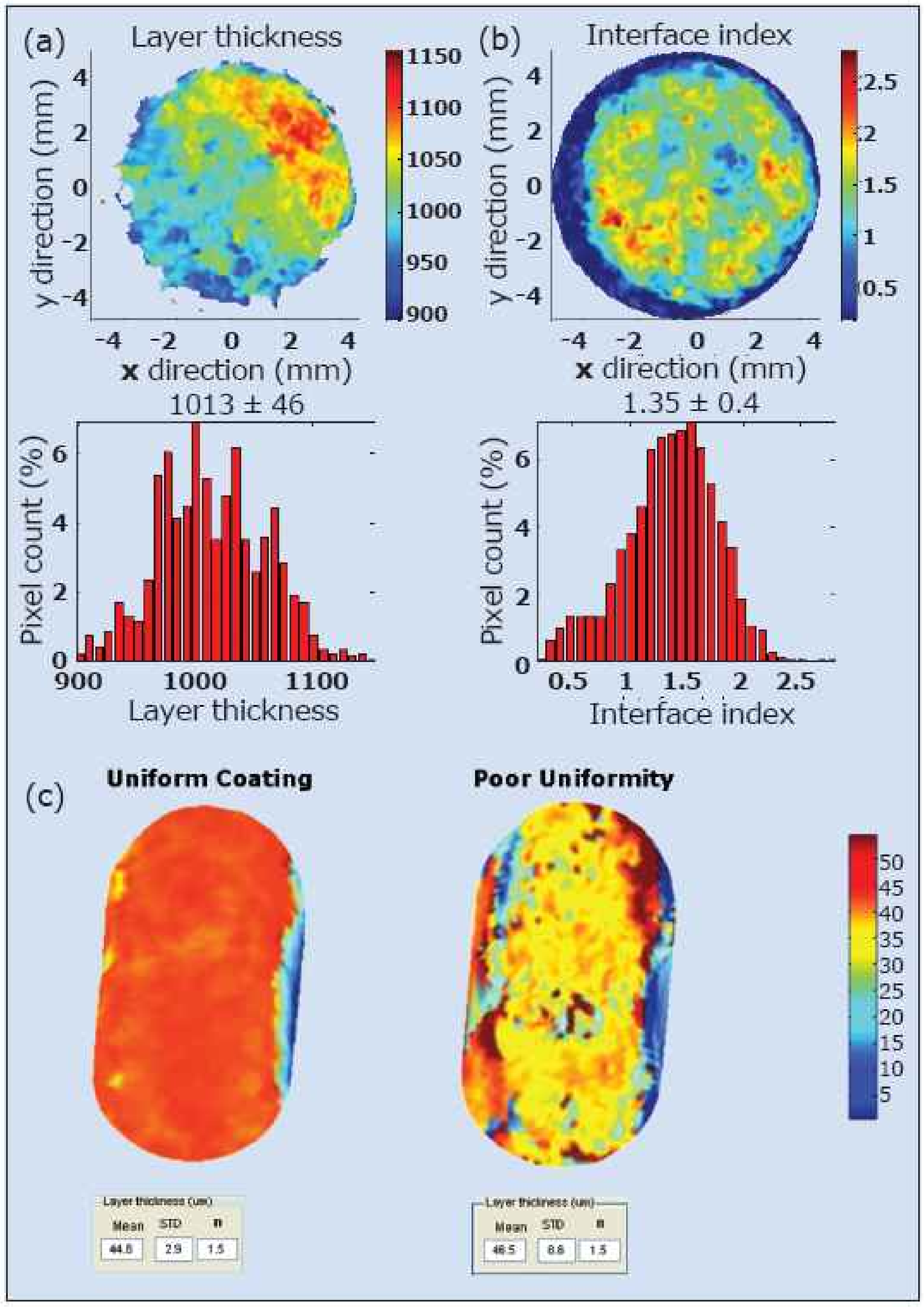

Figure 5: Images made with TeraView system on a buried layer in a pharmaceutical tablet coating. (a) Thickness map and histogram. (b) Interface index map and histogram give a view of the integrity of the interface between two layers. It shows there is some non-uniformity at the interface, particularly around the edges. (c) Color maps showing thickness variation in a coating applied to a tablet.

warming, total radiation balance, and pollution processes [5]. For example, the five-year Earth observing system microwave limb sounder (EOS-MLS) [6] launched on Aura, 15 July 2004, measures thermal emission from broad spectral bands centered near 118, 190, 240, 640 and 2250GHz using high-resolution heterodyne receivers [7]. Further, the strong emission lines at 183 and 557GHz for water have been proposed as potential signals for planetary life detection.

Water T-ray absorption could also be used to distinguish materials with varying water content (e.g. fat vs lean meat). Further actual and proposed THz applications include screening for explosive related chemicals (ERC) at airports (even at a 'standoff' distance of 30m [8]), plasma fusion diagnostics and non-destructive evaluation (NDE).

Some proposals have also been made for THz radar and communications systems. However, the atmosphere is generally opaque to T-rays, although there are some potential frequency windows, particularly at higher altitudes (e.g. in the stratosphere) where there is lower scattering and greater penetrating power through aerosols and clouds compared with infrared and optical wavelengths. THz also has potential for the development of better radar scattering signatures for objects through the use of scale models of objects that can then be extrapolated to RF and microwave systems.

T-ray generation

A number of techniques are used and proposed for producing terahertz radiation. As is often the case for radiation-producing systems, there are continuous wave (CW) and pulsed systems with different characteristics and applications.

A typical CW source is the optically pumped terahertz laser (OPTL). These are often gas lasers of narrow bandwidth. Although hydrogen cyanide (HCN) or methyl fluoride (CH_3F) can be used to produce terahertz radiation, it is perhaps not surprising that the much more benign CO_2 is more popular, and there are commercial systems available aimed at the THz market.

There have also been some proposals for optical pumping of semiconductor materials to produce THz. Vukmirovi et al [9] present a design and simulations of an optically pumped laser using a GaN/AlGaN double quantum well. The double-well structure sets up subband electron levels between which the transitions take place. The laser mechanism is based on a simple three-level scheme where the lower level is depopulated (creating the necessary population

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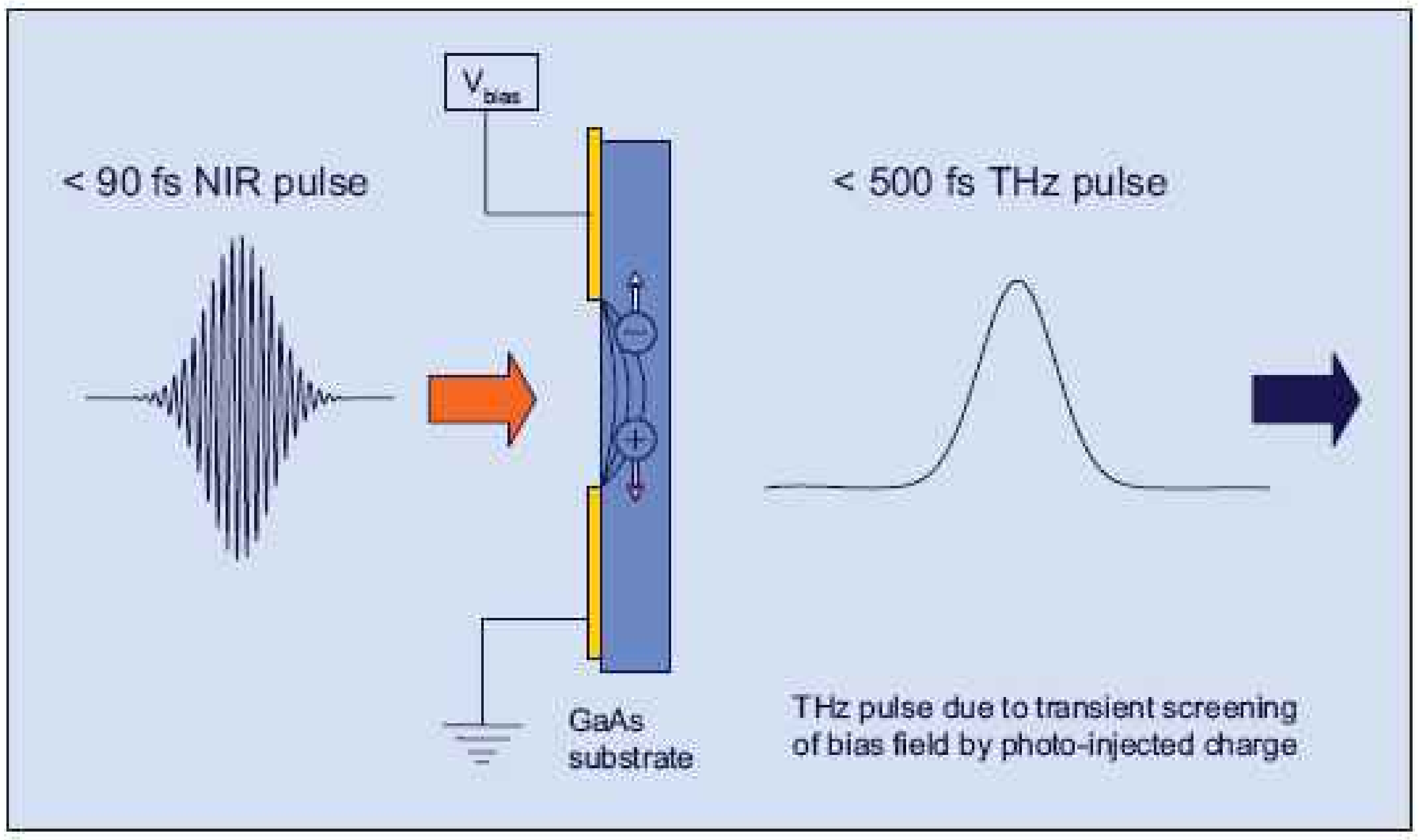

Figure 6: Laser gated photoconductive semiconductor for THz generation. Based on slide from TeraView.

inversion) via longitudinal optical phonon emission. An alternative material system, a $ZnSe/Zn_{1-y}Cd_ySe$ double quantum well with a $Zn_{1-x}Mn_xSe$ diluted magnetic semiconductor barrier, is presented by Popadi et al [10]. This OPTL (still theoretical) is also simulated. A giant Zeeman splitting takes place in the electron levels in the diluted magnetic semiconductor. An external magnetic field allows tunability of the laser in the range 60–72µm at low temperature.

A typical system for a pulse source consists of a gold split antenna switch structure fabricated on a GaAs substrate (Figure 6). TeraView uses such a system. A DC potential difference is set up across a gap in the structure. Pump laser pulses of duration less than 100fs are focused on the antenna gap. Photogenerated charge carriers jump the gap, with the current burst producing terahertz electromagnetic waves. Optical collection, collimation and focusing of the radiation produce a THz beam. Such sources give the broadband short-pulse radiation needed for time domain spectroscopy (TDS) and imaging, for example. Similar source systems use, instead of the GaAs photoconductive antenna, optical rectification (OR) in nonlinear media, where the high-frequency portion of the laser pulse is 'rectified' out to leave the THz radiation. OR materials include a number of patterned semiconductors (GaAs, GaP, ZnTe, GaSe), lithium niobate ($LiNbO_3$), and even metal surfaces. Photoconductive antennas can also be constructed out of (radiation-damaged) silicon or InP. Different pump lasers are suitable for different systems. For the GaAs antenna system, Ti:sapphire femtosecond lasers with a center wavelength of 800nm are often used, although a less expensive pump laser (e.g. laser diodes) would be desirable.

Another semiconductor system used to produce THz radiation is the quantum cascade laser (QCL). These have the advantage that they operate through current injection rather than optical pumping. Although QCLs were originally produced in the mid-infrared range (5.2µm) at Bell Laboratories [11], the principles can be extended to the terahertz range. QCL wavelengths vary from 3.5µm infrared (~0.4eV, ~80THz, ~400K) up to 160µm THz wavelengths (~8meV, ~2THz, ~90K) and beyond. Pushing to the lower (THz) end, there are a number of differences and complications, since the inter-subband transitions used to create the laser radiation needs to be much narrower (of the order of 1–4meV). The material system is commonly GaAs/AlGaAs or AlInAs/InGaAs heterostructures, although there has also been work on Si/SiGe, along with some of the other usual suspects, such as GaN, AlGaN, InP, GaSb, etc.

An advantage of the Si/SiGe combination is, of course, cost. However, another gain is possible higher-temperature operation, since there is no polar optical phonon to couple to in silicon and the coupling is negligible in SiGe, unlike with GaAs/AlGaAs systems. This is in contrast to normal laser diodes operating across the full bandgap, where Si and SiGe optical transitions are forbidden by the indirect bandgap of these materials and one is forced to use direct-bandgap materials such as GaAs/AlGaAs. However, it must also be remembered that, at present, these are theoretical considerations and, as yet, no working Si or SiGe QCL has been fabricated, although some non-lasing emission has been achieved.

Dr Douglas J Paul, senior researcher at the University of Cambridge, UK, is among those developing SiGe for QCL application. Paul comments: "With regard to the Si/SiGe cascades, we now have the waveguide losses down to a total value of $15cm^{-1}$ (including free-carrier absorption and mirror losses), which is similar to GaAs devices. However, while we have designs for the active region that have enough gain to overcome this value, we are still struggling to find a grower who can grow the structures accurately enough to achieve high gain. As the two programmes we have funded for this are drawing to a close, it's difficult to know if we can achieve this in the near future without more funding."

All these different QCL systems are generally cooled to the extent needed by the particular frequency and material basis. Some achievements include operation down to 1.39THz (by applying magnetic confinement) [12], operating temperatures up to 164K (pulsed) and 117K (continuous) [13], and peak powers of the order of 248mW (pulsed) and 138mW (continuous) [14]. Various techniques are used to improve the waveguide/cavity structure of the laser, such as distributed feedback, metal gratings and waveguides, surface plasmons, etc.

With the THz field still very immature, there are many other techniques being explored to generate THz. Further semiconductor-based methods include photo-mixing of near-IR laser light and frequency multiplier systems. In photo-mixing, infrared laser diode light can be mixed with tunable Ti:sapphire laser radiation using low-temperature-grown GaAs with an antenna structure to produce THz. Virginia Diodes, starting from GaAs Schottky diodes, uses a variety of techniques to increase fre-

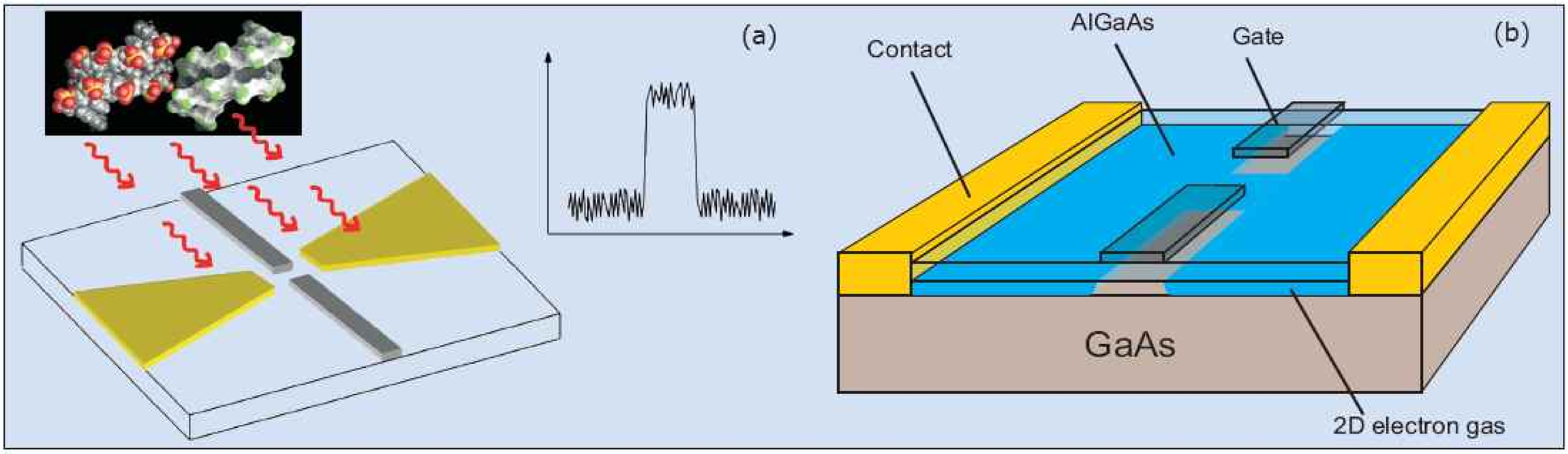

Figure 7: University at Buffalo's quantum point contact (QPC) detector: (a) grey and gold regions create a quantum point contact nanowire device that detects THz radiation emitted by targeted substance; (b) close-up.

quencies such as multiplier effects based on higher harmonics (up to x6). Non-semiconductor-based methods include backward-wave oscillators (BWOs), a sort of vacuum tube, and free-electron lasers that use high-energy electron beams to produce laser light.

Detectors

Many of the THz detection systems effectively use the above generation techniques in reverse. Hence, the photoconductive, optical rectification and inter-subband/quantum well (extending quantum well infrared photodetectors) technologies are often used. As with generation, one also finds non-semiconductor techniques such as detectors based on plasmonic techniques, and in addition many groups are researching superconducting detectors.

For spectral analysis, detection is often made through mixing the terahertz signal with a close known laser frequency (heterodyning) to produce a lower-frequency modulation that can be detected and then measured electronically. This requires a narrow-band CW laser such as the CO_2 OPTL.

Quantum point contacts (QPCs) are another semiconductor system being used to develop terahertz detectors by a team of scientists from the State University of New York at Buffalo, the University of California at Santa Barbara, and the Queens and Kingsborough Community colleges of the City University of New York [15]. These researchers hope that the confinement provided by the negatively biased metal contacts that raise barriers in the two-dimensional electron gas (2DEG) of a QPC and deplete the electron population in certain regions will enhance frequency resolution (Figure 7). The structure increases the coupling of the THz electromagnetic field to confined transitions in the 2DEG. A 2DEG, without such lateral confinement, normally has only weak coupling to electromagnetic waves that are incident perpendicular to the surface, since the fields are in the plane of the 2DEG. The carriers are then effectively free and the absorption is then 'bolometric' and lacks frequency resolution. ■

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