Electromagnetic alchemy

Antimony compounds have been used for cosmetic and other purposes since 3000BC and were common ingredients in alchemical formulations. Now, applications beckon for high-speed electronics, and for the detection and manipulation of infrared light and magnetic behavior, says Dr Mike Cooke.

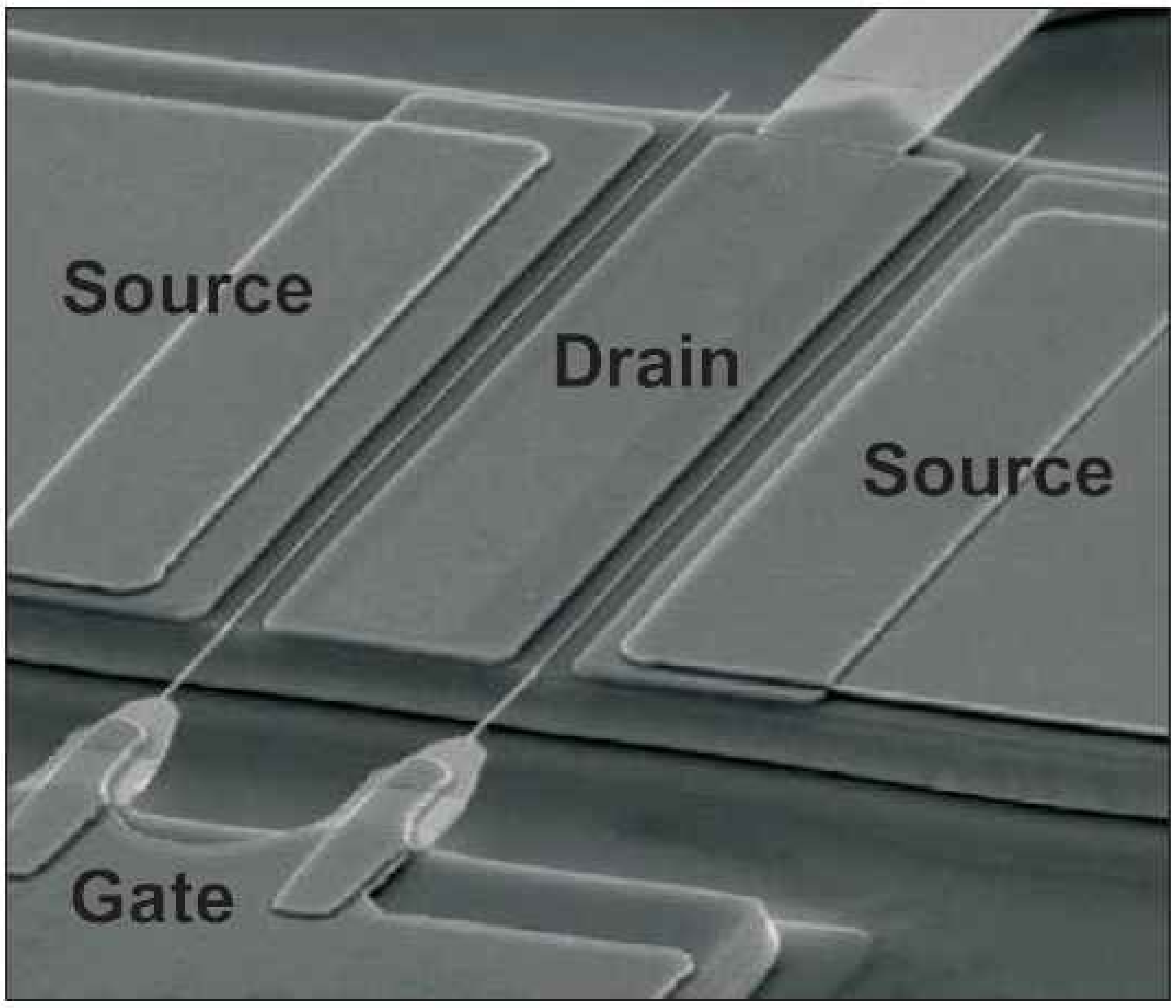

Figure 1. Image of Intel/Qinetiq two-gate finger InSb quantum well transistor.

In the last few years, antimonide semiconductor compounds have been of increasing interest for the creation of new high-speed electronics and for accessing infrared wavelengths unavailable to more common compound semiconductors. In addition, InSb's unusually high magnetic electron coupling opens up opportunities for magnetic field detection, electron spin manipulation and even the creation of quantum communications and computing devices.

Key properties of InSb are high mobility and saturation velocity based on the electron's small effective mass (~0.014m_0) and an unusually large (negative) electron Landé g-factor representing the electron's magnetic coupling (Table).

Digital antimony

Qinetiq, a UK firm focused largely on the defense market, is one of the leaders in applying InSb technology. In the electronic application field, Qinetiq has worked extensively with Intel on producing fast field-effect transistors (Figure 1) for use in possible future CMOS production. Impressive results have been achieved in producing n-channel FETs with fast switching speeds and low power drain compared with silicon-based devices in both depletion mode and enhancement mode, based on InSb's high electron mobility and saturation velocity.

The enhancement-mode devices (normally-off, as employed in CMOS) use a recessed gate structure (an uncooled 85nm device shows a 10-fold reduction in active power dissipation and 1.5-fold increase in speed compared with silicon MOSFETs). A further requirement on which good progress has been made is in producing devices on silicon (Figure 1 of reference [2]) rather than on III-V substrates [3]. Silicon integration is needed not only for integration into existing CMOS infrastructure but also because low-cost devices need to be produced on the largest possible substrate for high volume production — and that means producing on silicon with the largest diameter (currently 300mm, and in future this may reach 450mm). III-V substrates have not yet reached 200mm diameter in volume production, with 150mm GaAs substrates being the largest currently in routine production.

Mike Mayberry, director of Components Research at Intel's Technology & Manufacturing Group, reports that Intel has broken down the problem of integrating III-V materials into CMOS production as five sub-problems:

Table 1. Comparison of properties of common semiconducting materials and InSb and GaSb.

	Units	Silicon	GaAs	$In_{0.53}Ga_{0.47}As$	InAs	InSb	GaSb [1]
Energy gap	eV	1.12	1.43	0.75	0.356	0.175	0.726
Electron effective mass	m_0	0.19	0.072	0.041	0.027	0.013	0.041
Electron mobility in pure material	cm^2/Vs	1,500	8,500	14,000	30,000	78,000	>3000
Electron saturation velocity	cm/s	1.0×10^7	1.2×10^7	8×10^6	3×10^7	5×10^7	8×10^6
Intrinsic carrier concentration	cm^{-3}	1.6×10^{10}	1.1×10^7	5×10^{11}	1.3×10^{15}	1.9×10^{16}	1.5×10^{12}
g-factor		2	−0.5	−5	−15	−51	~−10

- integration on silicon substrates;
- finding a suitable high-k dielectric;
- making PMOS devices;
- creating enhancement-mode rather than depletion-mode devices;
- miniaturization.

Mayberry believes it is too early to say what a final process would be like for producing III-V channel CMOS devices, although the leading contenders at this time are InSb and InGaAs. InSb has the attraction of high mobility, while InGaAs has been studied more extensively (at MIT, among other places).

While there are promising results in producing PMOS quantum well devices through applying strain to boost p-type mobility, says Mayberry, there is nothing publishable as yet. He agrees that, while it is possible to use different materials for the different transistor channels, integration with the same material would be preferable from a process simplicity perspective. Some groups have studied, for example, the possibility of combining germanium and InGaAs devices, despite the process mismatch.

Along with the Qinetiq work [3], an Intel collaboration with IQE [4] on InGaAs devices resulting from growing III-V layers on silicon substrates has recently been published. The Qinetiq work relates in particular to InSb quantum well channels in a field-effect transistor structure. An 85nm InSb channel device on silicon had a unity current gain cut-off frequency of (f_T) of 305GHz at an operating voltage (V_{dd}) of 0.5V. The buffer layer system designed to overcome lattice mismatches between the silicon and device levels was 1.8μm thick. A similar $In_{0.7}Ga_{0.3}As$ device has an f_T of 260GHz at 0.5V with a 3.2μm buffer between the silicon substrate and device layer.

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Presently, molecular beam epitaxy is used to grow the necessary buffer layers and devices, with experiments performed at the 'coupon' level, on fragments of silicon. In terms of scaling up production, Mayberry reports that some other Intel partners are exploring non-MBE techniques for growing III-V layers on silicon. However, this does not rule out the historically slow MBE from being the final process: many processes routinely used in semiconductor mass production started off as low-throughput methods in the lab or small-scale production.

On gate dielectrics, as for PMOS devices, there are some 'promising' but not yet publishable results. Another aspect of the problems concerning the gate dielectric and metal is being dealt with from the theoretical direction of mathematical interface models.

Silicon has been at an advantage, since silicon surfaces consist of a single element, and these surfaces are relatively easy to oxidize to a uniform quality. Compound semiconductors, consisting of a number of different elements, can have very complex surface state structures with different reactivity properties with oxygen and other chemicals that can lead to dielectric layers. Interface states can alter the performance of semiconductor devices — for example, charged interfaces can act like unwanted gate potentials. In addition, one wants a high-k dielectric that is stable on the device surface.

Mayberry believes that these problems are difficult, but not insurmountable [5].

Photonics

Apart from digital electronics, InSb's properties also have very high-frequency analog and photonic promise [2]. In particular, the narrow bandgap of InSb (0.175eV) and the more complicated alloys are used to detect and create infrared light in the 3–5μm wavelength range. Qinetiq, again, has produced InSb-based two-dimensional 'focal plane arrays' in standard formats (e.g. 1024x768) of infrared photodetectors for thermal imaging camera applications.

For mid-IR (3–5μm) quantum well lasers, Qinetiq has used a particular mélange of $Al_xGa_yIn_{1-x-y}Sb$ elements. Researchers from Qinetiq and the UK universities of Bristol, Surrey and Lancaster see the material system as offering great promise in terms of making the necessary compromise between the needs of electron and photon confinement and for low series resistance. Theoretical work suggests that the use of compressively strained Type-I wells will lead to the suppression of non-radiative transitions such as Auger recombination (assisted by a third particle) and inter-valence band absorption.

Qinetiq's diode lasers were grown on semi-insulating GaAs substrates using MBE. The choice of a GaAs substrate was due to the aim of eventual compatibility with commercial rather than laboratory production processes. Compressively strained InSb-like wells were deposited between confining layers of $Al_{0.12}Ga_{0.12}In_{0.76}Sb$ with $Al_{0.25}In_{0.75}Sb$ cladding (Figure 2). Laser mesas with a width of approximately 20μm were wet etched down to the lower cladding layer. Then SiO_2 passivation and insulation covered the devices, except for the top and side contacts. The laser mesas were cleaved to give devices with a length of either 1 or 2mm. The wavelength of the electroluminescence emission peak shifted with changing temperature from 3.4μm at 15K to 3.9μm at 250K. The researchers are targeting operation at even higher temperatures. Possible applications include free-space optical communications, taking advantage of low atmospheric absorption and scattering of wavelengths in the range 3–9μm.

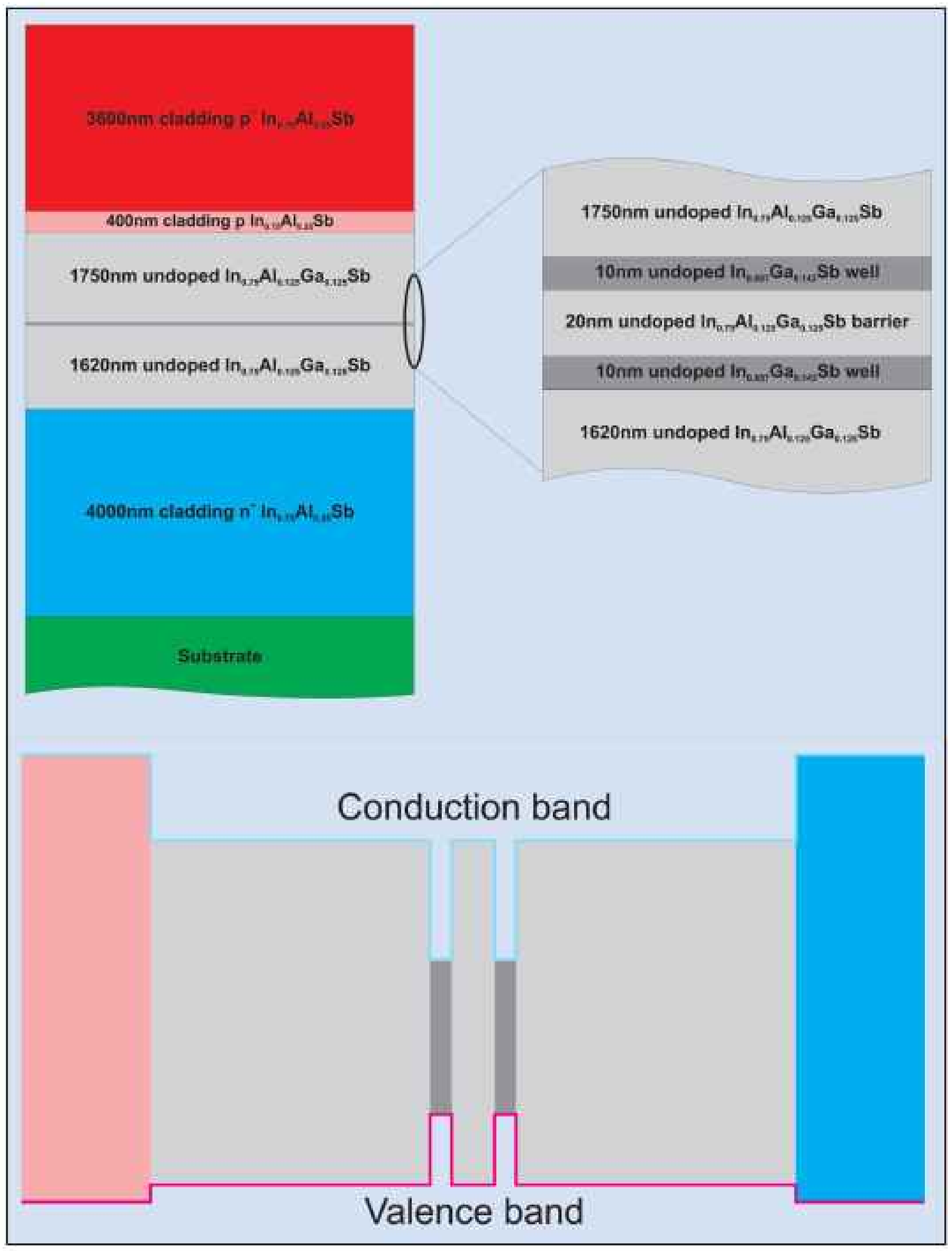

Figure 2. Layer structure of Qinetiq InSb based quantum well laser (top). Band diagram of quantum well structure of Qinetiq InSb based laser (bottom).

Yet another aspect for antimonide materials is the possibility of reducing the bandgap even further by using the band bowing effect of nitrogen at dilute concentrations. Warwick University has worked with Qinetiq on the growth and characterization of such materials for longer-wavelength applications. GaNSb and InNSb have been grown on GaSb and GaAs substrates. The GaNSb that was produced shows p-type behavior, with carrier concentrations in the range 3–6x10^{18}cm^{-3}. In contrast, InNSb is n-type, with carrier concentrations of ~2.5x10^{18}cm^{-3}.

While the materials are of 'good' quality with nitrogen content <1.75% for GaNSb and <0.68% for InNSb, the latter material is quite difficult to grow due to a narrow growth temperature window. A band filling effect from the higher carrier concentrations in InNSb creates difficulties in using the narrowed band gap for optical purposes. The absorption edge actually shows an increase in photon energy with increased nitrogen content rather than a decrease. An annealing step can reduce the carrier concentration and thus lower the absorption edge for lower nitrogen concentrations (~0.1%).

Another approach to photonics — InSb nanowires and nanodots — has been explored by Toyo University in Tokyo, Japan. The growth technique involves vapor transport onto a silicon substrate with the aid of a focused ion beam apparatus. Raman spectra, where photons lose and gain energy from vibrational and other state transitions, have been used to characterize performance. The researchers are particularly interested in looking for the size effects on carrier dynamics in nanodot and nanowire structures, allowing energy level and other manipulations for applications.

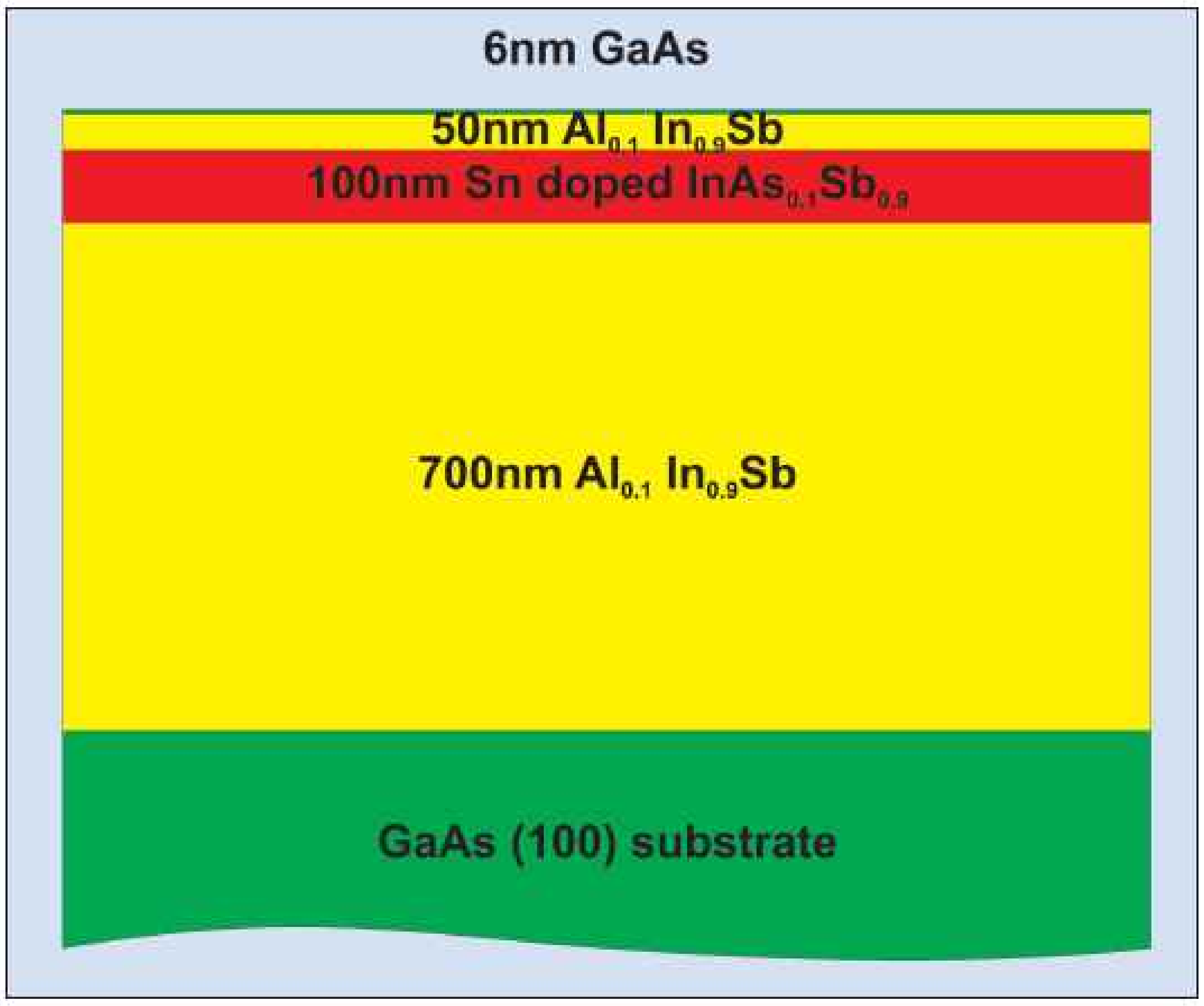

Figure 3. Schematic of Asahi Kasei's tin-doped antimony-based Hall sensor with improved mobility and temperature dependence.

Magnetics

Two aspects arise in connection with magnetism in antimonide semiconductors: the Hall effect and the electron Landé g-factor. The Hall effect — where a magnetic field applied to a slab of semiconducting material induces a transverse potential difference across the slab — is widely used to probe the charge carrier densities and mobilities in semiconductors. Conversely, where these properties are well established, Hall effect sensors can be used to measure the magnetic field intensity. Hall sensors are widely used in the control of electric motors, washing machines and for hybrid cars.

Asahi Kasei's Ichiro Shibasaki described his company's use of AlInAsSb thin films in Hall effect magnetic sensors at July's Thirteenth International Conference on Narrow Gap Semiconductors (NGS-13) [2]. In addition to the previous applications, Shibasaki sees opportunities in producing mouse-like functionality in advanced mobile phones.

The large mobility of InSb suggests the possibility of making very sensitive magnetic field sensors. For use in motor vehicles and other applications, one also needs a greatly expanded operating temperature range (from −40°C to +150°C instead of from 0°C to +100°C). Another attraction of InSb is that it has the

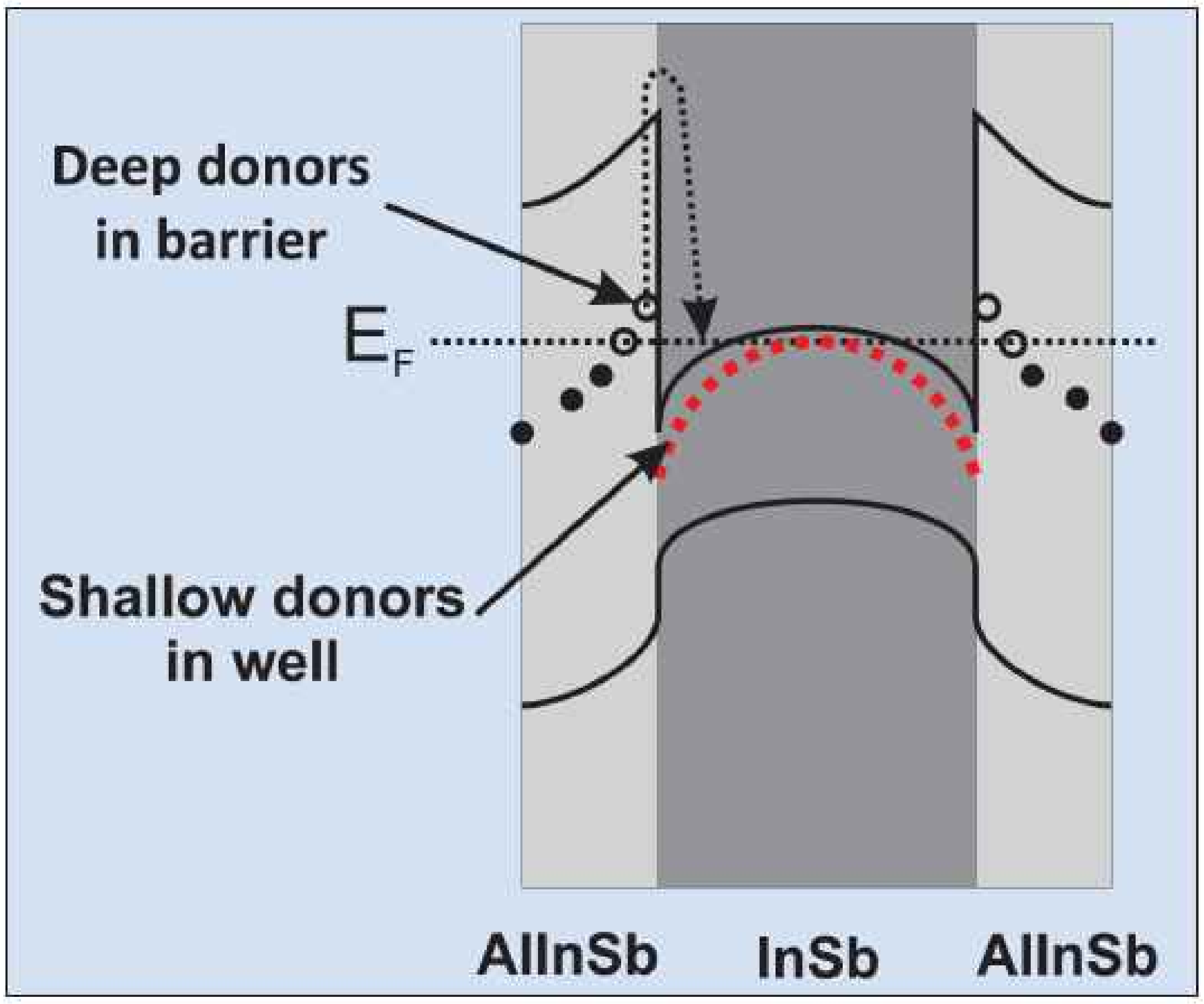

Figure 4. InSb quantum wells can suffer from deep donor levels in barriers tossing low-mobility 'extrinsic' electrons into the well.

advantage of a small temperature dependence of its properties.

On its own, InSb has a 14% lattice mismatch with GaAs substrates, which impacts mobilities for films thinner than 500nm (by a reduction of 50% or more). Fabrication processes such as deposition of Si_3N_4 or SiO_2 (e.g. insulation, passivation) can also damage InSb. To overcome these problems, Asahi Kasei has been experimenting with layered structures such as GaAs(6nm)/$Al_{0.1}In_{0.9}Sb$(50nm)/$InAs_{0.1}Sb_{0.9}$(15–500nm)/$Al_{0.1}In_{0.9}Sb$(700nm) for creating quantum well Hall effect devices by MBE. $Al_{0.1}In_{0.9}Sb$ is insulating and lattice matched to $InAs_{0.1}Sb_{0.9}$. The thin insulating layer of GaAs is a top layer designed to protect the structure from further processing damage. The Asahi Kasei work resulted in great improvements in mobility, Shibasaki reports. Doping with tin can also improve the temperature dependence of devices (see Figure 3).

Although very useful in probing semiconductor properties, the Hall effect does not exhaust the utility of magnetism. With InSb, the electron's g-factor (the effective magnetic moment) has a surprisingly large negative value, opening avenues to even more detailed information regarding the material's properties, with application, for example, to determining hole properties to help with looking for p-channel devices to complement those of n-channel FETs [2].

Japanese researchers (Osaka Institute of Technology, Tokyo University of Science, Asahi Chemical, and Chiba University) have also been working on the magnetic properties of non-doped $Al_xIn_{1-x}Sb$/InSb quantum well structures. These perpendicular and parallel magnetoresistance investigations were aimed at determining the well-width dependence of extrinsic electrons and carrier accumulation in $Al_xIn_{1-x}Sb$/InSb QWs.

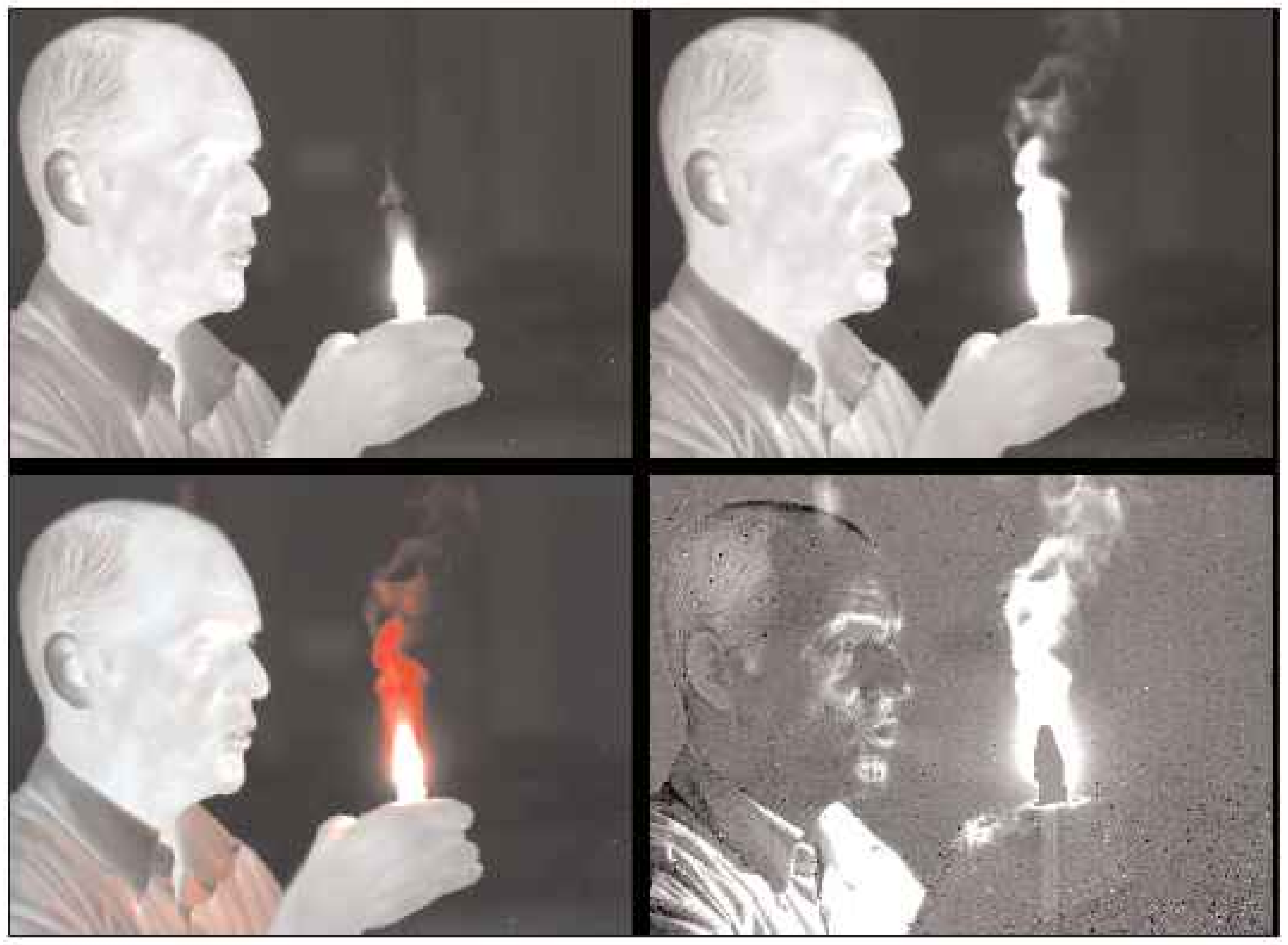

Figure 5. Thermal image of Dr Martin Walther holding a burning candle from Fraunhofer IAF's two-color IR imager: (top left) with a cut-off wavelength of about 4.2µm — the so-called blue-channel, longer wavelengths are not detected; (top right) detecting the whole spectral range up to 5µm — the so-called red-channel; (bottom left) fusion of both pictures, giving an impression of how to create 'real' color photos in the infrared (the complementary colors red and cyan are used for the two channels: objects emitting infrared radiation in both channels appear 'white', whereas objects emitting only in the long-wavelength channel appear 'red') — the hot CO_2 created by the burning candle and the reflection on Walther's shirt are clearly seen; (bottom right) differential picture, created by subtraction of blue and red channels — objects emitting IR radiation of comparable intensity in both channels therefore appear dark (looking closely at this picture one can see the CO_2 in Walther's breath).

'Extrinsic electrons' come from deep donor levels in barriers and can accumulate at heterointerfaces, even when neither the InSb well nor the barrier region ($Al_xIn_{1-x}Sb$) are deliberately doped (see Figure 4). These electrons have extraordinarily small mobility — not good when the purpose is to create high-mobility characteristics. To try and probe this problem, the Japanese researchers carried out Hall and magnetoresistance measurements on $x = 0.1$ QWs grown on GaAs substrates. This value of x gives a lattice mismatch between the well and barrier as small as 0.5%. The magnetic field dependence of the Hall constant at 77K suggests the presence of two types of electron with different mobilities: one type emanating from the well region and the other from the heterointerfaces. At room temperature, the two-carrier model analysis suggests that the sheet density of the extrinsic carriers from the heterointerface decreases with increasing well widths above 100nm in the shallow wells that were investigated.

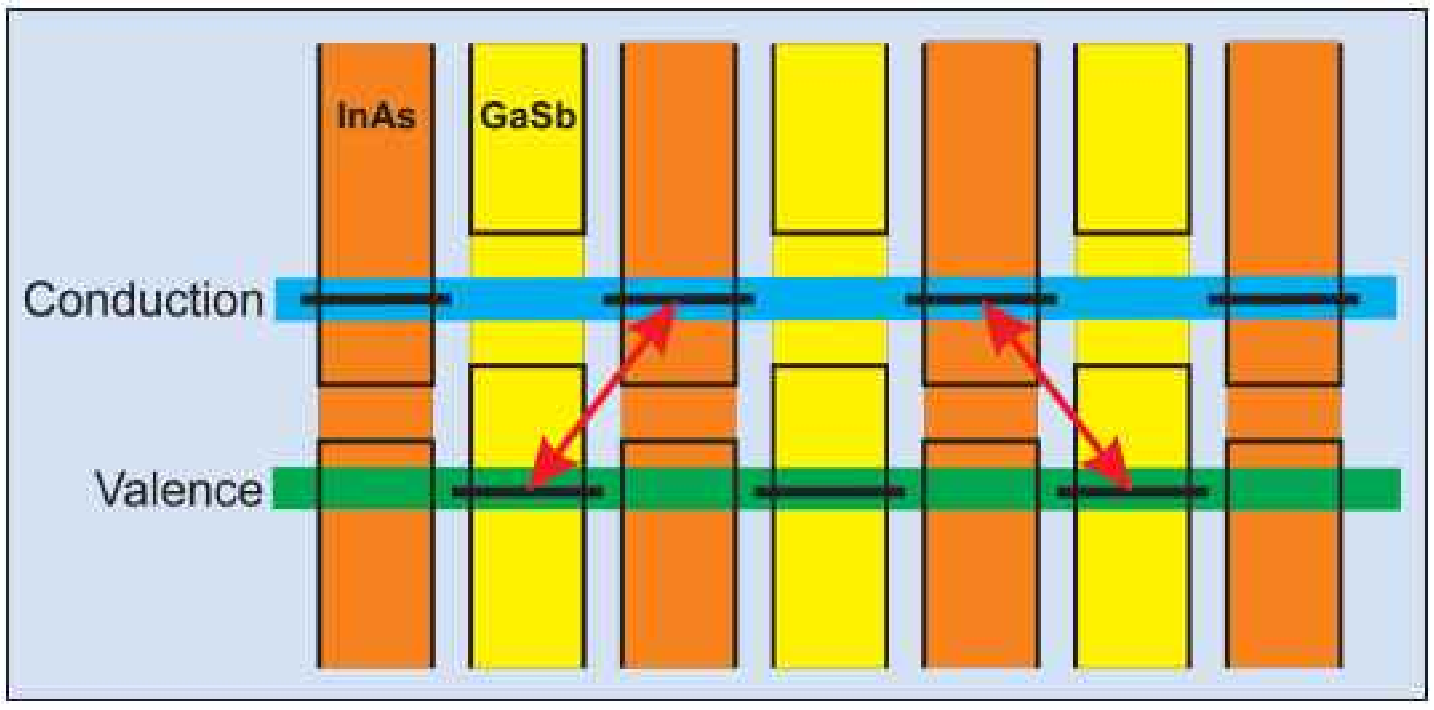

Figure 6. Superlattice system used in Fraunhofer IAF's thermal imagers.

The large negative electron g-factor in InSb also raises hopes of using spin to create a new dimension in electronic devices (spintronics). Quantum well heterostructures in Datta–Das-type spin-FETs and spin filter formations are the aim of joint work between Imperial College London and Qinetiq. Among the requirements for these applications are a long spin diffusion length, long spin lifetime and high mobility.

Sb substrates

Apart from producing epitaxial antimonide semiconductor layers on silicon or GaAs wafers, GaSb and InSb substrates can also be produced. One clear advantage of using such wafers is lattice matching with particular epitaxial layers.

One company producing such substrates is the epitaxial substrate producer IQE, which has production facilities in the UK and the USA. This company has a range of GaSb substrates available from its Wafer Technology division in Milton Keynes, UK. Wafer Technology also has InSb wafers of 50mm and 75mm diameter with a 100mm product 'under development'.

IQE's epitaxy-ready GaSb substrates (50 and 75mm) have been exclusively used in award-winning research and development at Fraunhofer IAF of Freiburg, Germany into InAs/GaSb based two-color thermal (infrared) imaging cameras (Figure 5). This research won Fraunhofer IAF the 2006 Baden-Württemberg research prize (which is worth €100,000).

Fraunhofer IAF used MBE to deposit InAs/GaSb type-II superlattices (SL), creating the bi-spectral infrared imaging system (Figure 6). The 'blue' channel senses radiation with wavelengths in the range 3–4μm, while the 'red' channel detects 4–5μm photons. These wavelengths correspond to black-body temperatures of the order 5000K. The noise equivalent temperature differences of the 'red' and 'blue' pixels are 17mK and 30mK, respectively. By combining the 'red' and 'blue' pixels in a 288x384 array (40μm pitch), the camera overcomes the typical registration problems common to existing multi-spectral cameras that combine different 'color' data from separate sensor arrays. The performance of the new system compares with that of state-of-the-art mercury cadmium telluride (MCT)-based systems.

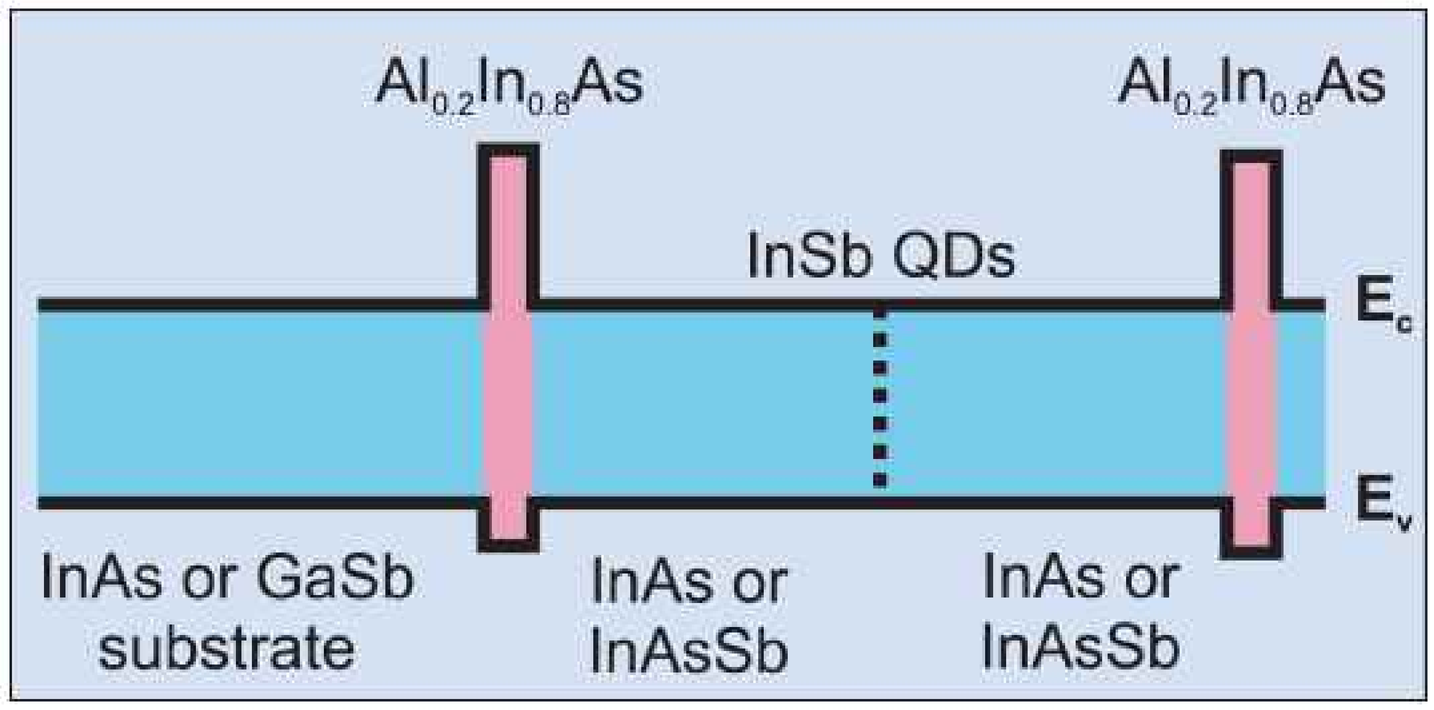

Figure 7. InSb quantum dot layer is formed by short-time (20s) exposure of heated InAs surface to Sb flux, leaving a monolayer that forms InSb islands with a density of $\sim 10^{12}$cm^{-2}.

The dual-color superlattice detector will be the sensor used in the Multi-Color Infrared Alerting Sensor (MIRAS) system of the new European A400M large military transport aircraft. The MIRAS system is being developed by European Aeronautic Defence and Space (EADS) and Thales.

Fraunhofer IAF researcher Dr Martin Walther comments: "Our new infrared detector is ideally suited for new state-of-the-art early-warning defense systems and, as such, has a big market potential within the civil and military aviation industry."

At the NGS-13 conference, Alexey Semenov described investigations into growing InSb quantum dots on GaSb (and InAs) substrates using MBE at the Ioffe Physico-Technical Institute in Russia (Figure 7). The researchers hope that the greater overlap between the electron and hole wavefunctions compared with QWs could lead to laser devices. InSb QDs show photoluminescence in the wavelength range 3.9–4.4μm.

As reported elsewhere in this issue [2], the US Naval Research Laboratory (NRL), France's Université Montpelier and Germany's Walter Schottky Institute are other developers of devices that use GaSb substrates. Montpelier's devices use the high conduction band offset (2.1eV) offered by AlSb/InAs structures on GaSb substrates to create high-temperature, short-infrared-wavelength (i.e. <5μm) QCLs. The Walter Schottky Institute in Munich uses zinc-doped GaSb substrates in its development of electrically pumped GaSb-based VCSELs. ■

References

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[5] More details of Mayberry's perspectives can be found at http://blogs.intel.com/research/2007/08/enforcingmooreslaw.html