compensated by angular frequency shift $\delta\omega$ of a higher-harmonic wave:

$$\Gamma_{\mathrm{opt}}\Omega + \frac{P\delta\omega}{n\omega_{\mathrm{F}}} = 0 \qquad (4)$$

where P is incident average power and Γ_{opt} is the amplitude of the optical torque (directed along the propagation direction) exerted on the nonlinear crystal that can be derived by evaluating the optical spin angular momentum transfer to matter, as each photon of a circularly polarized wave with helicity σ carries $\sigma\hbar$ angular momentum along the propagation direction ($\hbar$ is the reduced Planck constant):

$$\Gamma_{\mathrm{opt}} = (\sigma_{\mathrm{F}} n - \sigma_{\mathrm{HH}})\frac{P}{n\omega_{\mathrm{F}}} \qquad (5)$$

Combining equations (4) and (5) above, one obtains equation (4) of ref. 3 while preserving the condition of a constant Ω, which is expressed with the present notation as

$$\delta\omega = -(\sigma_{\mathrm{F}} n - \sigma_{\mathrm{HH}})\Omega \qquad (6)$$

It is worth mentioning that the experimental manifestation of a rotational Doppler effect was demonstrated 20 years ago in a nonlinear optics experiment[4] by irradiating a thin film (tens of micrometres thick) of liquid crystals by a continuous-wave circularly polarized laser beam. However, a few differences between this experiment and the one reported by Li *et al.* should be emphasized. First, the rotational Doppler effect reported in ref. 4 results from a self-induced nonlinear phenomenon, the nonlinear medium being rotated by the light itself. Such a situation would hardly be observable in the approach of Li *et al.* even though the optical torque exerted on the medium per incident 'working photon' is larger than in ref. 4 by a factor 3/2, because of the extremely low efficiency of the nonlinear process mentioned above and the macroscopic size of the nonlinear crystal. Second, the nature of the nonlinear process is orientational in ref. 4 and does not involve the generation of a new wave, whereas the electronic nonlinearity at play in the work of Li *et al.* leads to the generation of a second-harmonic wave.

Remarkably, the generation of additional waves via electronic nonlinearities that are not restricted to quadratic nonlinearity as experimentally explored by Li *et al.*, provides access to enhanced rotational Doppler shifts[3]. This could lead to the development of contactless, sensitive, nonlinear optical detection of rotational motions, although the signal level is an issue that remains to be solved before practical implementation involving higher harmonics is possible. Accordingly, it would be interesting to explore whether a quasi-phase-matching strategy, a well-developed technique in laser physics that involves spatial modulation of the material nonlinearity to obtain highly efficient harmonic generation, could be implemented.

Only the spin contribution to the optical angular momentum has been mentioned so far, thus an open question is related to the possible role of the orbital angular momentum. In particular, spin–orbit interaction of light, which couples the polarization degree of freedom to the spatial degrees of freedom of light fields[5], may lead to enhancement of the rotational Doppler effect. To this end, an option building on the scheme used by Li *et al.*, where light propagates along the optical axis of a crystal with discrete rotational symmetry, could be to enrich the angular spectrum content of the fundamental field. Indeed, previous works considering nonlinear harmonic generation of Bessel beams[6] suggest intriguing interplay between spin and orbital angular momentum of light. Finally, it would also be interesting to explore the generic features of the rotational Doppler effect by extending the proposed approach to other kinds of waves. ❐

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PHOTODETECTORS

The staircase photodiode

The demonstration of a prototype avalanche photodiode with a staircase band profile suggests that such devices may ultimately become a viable alternative to photomultiplier tubes in the infrared.

John David

The search for a semiconductor equivalent of the photomultiplier tube (PMT) that operates in the infrared spectral region (defined here loosely as wavelengths >1 μm) has been a long-standing quest of many photodetector researchers.

Photomultiplier tubes offer the attractive attributes of high sensitivity, extremely low noise performance and low timing jitter. However, they are usually based on a vacuum tube design and as such are inherently fragile, need high voltages, are susceptible to magnetic fields, and are relatively bulky and expensive. As a result, they tend to only be used in applications where having the best performance possible is critical and the development of a cost-effective, semiconductor alternative that offers similar functionality is highly desirable.

For photodetection tasks in the visible and near-infrared region, semiconductor-based avalanche photodiodes (APDs) are now fulfilling this role. They are small, relatively cheap, operate at modest voltages, and for light detection below 1,100 nm, silicon-based arrays of single-photon-counting detectors (silicon photomultipliers or SiPM) are replacing traditional PMTs. However, at longer wavelengths, APDs based on narrower-bandgap semiconductor materials are necessary and the sensitivity of these photodetectors is severely limited by the presence of high noise.

A recent paper by Ren *et al.* in *Applied Physics Letters*[1] now suggests that a semiconductor photodetector with PMT-like behaviour in the infrared

could be possible. They have shown that electrons travelling from a wider-bandgap semiconductor material into a narrower-bandgap material can gain the energy difference between the conduction bands (Fig. 1a), thereby significantly reducing the energy needed for an ionization process to occur and consequently almost doubling the photogenerated current. In principle, by undertaking clever bandgap engineering, this process can be repeated many times within one device and provide a PMT-like performance without the attendant disadvantages.

In a PMT, light falls on a photocathode, creating electrons that are accelerated in a vacuum to impinge on a series of successive dynodes where further charge-carrier multiplication occurs, resulting in a large current. Avalanche photodiodes (essentially a reverse-biased semiconductor p–n or p–i–n junction) also amplify an initially created photocurrent via the impact ionization process. However, unlike PMTs where only electrons exist, and these are multiplied only at the dynodes, semiconductors have both electrons and holes that are capable of being ionized anywhere within the high electric field, and the stochastic nature of the impact ionization process leads to 'excess' noise at high gains. That this high level of noise is due to both charge carriers being ionized was realized by Robert John McIntyre from the company RCA Electro Optics in the 1960s[2] who quantified the process and showed that ideally only one carrier type in a semiconductor should undergo impact ionization in order to minimize the detector's noise.

In the 1980s and early 1990s, there was a flurry of activity attempting to exploit the concept of band-structure engineering, using semiconductor heterojunctions as a way of ensuring that only one carrier type underwent impact ionization. In conventional APDs, carriers undergo impact ionization with a uniform probability in a constant high-field region. By utilizing the conduction-band discontinuity of a heterojunction, the probability of ionization is increased significantly just after an electron enters a narrow-bandgap semiconductor from a wider-bandgap semiconductor, thereby mimicking the behaviour of a dynode in a PMT.

In 1980, a team of researchers from the University of Illinois at Urbana-Champaign[3] theoretically suggested the use of GaAs/AlGaAs multilayer structures to enhance the ionization properties of electrons over that of holes. As the conduction-band discontinuity was much

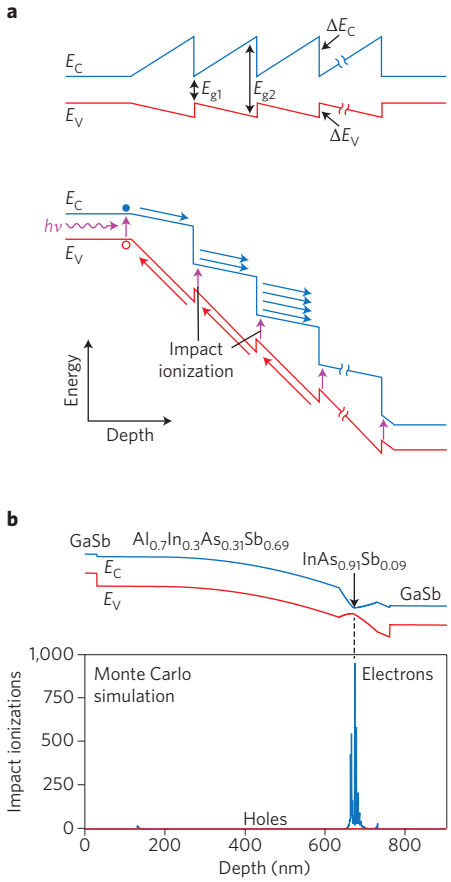

Figure 1 | Principle and realization of a staircase APD. **a**, The band structure when under no bias (flat band; top) and when biased (bottom). As ΔE_V is relatively small, holes will not get trapped at the interfaces of each step. E_V and E_C are the valence- and conduction-band energy levels, respectively, and E_{g1} and E_{g2} are the bandgap energies of the narrow-bandgap and wide-bandgap semiconductor, respectively. Filled circle, electron; open circle, hole. **b**, A one-step heterojunction staircase APD under bias. Note the grading at the interfaces. The graph shows that the electron ionization is highly localized within the narrow-bandgap material $InAs_{0.91}Sb_{0.09}$. Figure reproduced with permission from ref. 1, AIP Publishing LLC.

larger than that of the valence band in a GaAs/AlGaAs heterojunction, electrons falling from the AlGaAs into GaAs would gain the extra energy of the conduction-band discontinuity, thereby reducing the energy required for electrons to ionize in the GaAs layer. In a multilayer structure, the electrons therefore preferentially ionize much more readily at each step than holes, resulting in a large asymmetry in the ionization of electrons with respect to the holes.

Two papers from Bell Labs followed in quick succession exploring this concept in more depth[4,5]. Capasso *et al.*[4] were the first to report experimental results of the electron- and hole-initiated avalanche multiplication in a 25-period GaAs/AlGaAs multilayer structure. A paper by Williams *et al.*[5] then featured the first suggestion of using graded bandgap layers, which under bias would give rise to a 'staircase'-like conduction-band profile. The advantage of a structure with a staircase band profile over that of the more conventional multilayer structures is that having ionized, carriers are not trapped in the narrow-bandgap semiconductor. The structures described in both these papers had to be designed carefully such that at the electric field of operation, the electrons only ionized in the narrow-bandgap GaAs after gaining the conduction-band-discontinuity energy. Both these papers were cited dozens of times in the following years with several studies providing a theoretical basis for the ionization enhancement claim, and one-off reports of similar behaviour in other III–V multilayered material systems. However, with no incontrovertible evidence that such modification of the ionization properties was possible, interest in this idea diminished from the early 1990s.

The recent work by Ren *et al.*[1] describing a single-step staircase APD revisits this idea and describes what happens when photogenerated electrons travel in a wide-bandgap semiconductor, AlInAsSb, and then 'fall' into a narrow-bandgap semiconductor, InAsSb. The difference in the conduction-band energies at the AlInAsSb/InAsSb interface is 0.6 eV. This is important as the threshold energy for carriers to ionize and create a secondary electron–hole pair in the InAsSb is thought to be only ~0.375 eV. Compared with a control structure where the InAsSb was not present, the current they measured increased by a factor 1.8 ± 0.2 between the wavelengths of 400 and 950 nm.

These observations seem to make sense. If every electron entering the InAsSb gained the 0.6 eV energy and underwent impact ionization, one would expect to see a doubling of the current. Modelling of the structure showed that electrons underwent strong ionization when they entered the InAsSb (Fig. 1b) whereas holes did not appear to undergo any significant ionization. Thus Ren and colleagues' latest results do appear to be an experimental demonstration of what was originally postulated over 30 years ago[3–5].

The reason that this effect has been seen clearly in this material system and not in the earlier studies with GaAs/AlGaAs structures is due to the characteristics of the conduction bands in these materials. Czajkowski *et al.*[6] described how in

semiconductors such as GaAs and AlGaAs, charge carriers rapidly transfer out of the lowest conduction band to reside in higher-energy states before gaining sufficient energy to impact ionize, and the advantage of the conduction-band discontinuity is lost.

In view of the numerous experimental and theoretical reports that have previously heralded a solid-state PMT, it is worth asking how plausible the results and interpretation reported by Ren and colleagues are. There are certainly grounds to be optimistic. It is known that large conduction-band offsets can exist between two dissimilar materials. Work undertaken by several groups (including at the University of Sheffield) has shown that in narrow-bandgap semiconductor materials such as HgCdTe and InAs, only electrons seem to ionize and they do this at very low threshold energies. It is thus easy to understand why a better performance could be obtained by the structure shown in Fig. 1b that tends to spatially localize the ionization process in the narrow-bandgap material. In short, this photocurrent enhancement mechanism is entirely feasible.

However, the technological challenges that must be overcome before realizing a true solid-state PMT must not be underestimated. Although a doubling of the photocurrent is certainly valuable, to achieve true PMT-like performance will require multiple repeats of this AlInAsSb/InAsSb staircase heterojunction (Ren and colleagues' work reports just a single-step staircase) within the APD (necessitating the application of high voltages). In addition, the fine details of the multiple interfaces have to be controlled precisely and finally the background doping throughout the structure will need to be controlled very accurately. Another fundamental issue is that the dark currents in these narrow-bandgap materials can be large at room temperature and devices will need cooling to reduce this to acceptable levels. Despite these obvious problems, it does finally look like that the performance of semiconductor APDs can be substantially improved to start to mimic the behaviour of a classical PMT. As is often the case, it is likely to be the financial investment needed rather than fundamental problems with the device physics that may preclude the appearance of a semiconductor-based PMT in the near future. ❐

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OPTOMECHANICS

Vibrations copying optical chaos

Mechanical oscillation in a microtoroidal optical cavity transfers chaos from a pump to a probe laser beam with a different wavelength. Through stochastic resonance, the combination of noise and internal chaotic dynamics leads to amplification of optomechanically induced light self-oscillations.

Marc Sciamanna

The interaction between a light wave and the mechanical vibration of a macroscopic object — the study of which is known as optomechanics — results in a low-dimensional system showing nonlinear dynamics[1]. In a standard optomechanical set-up, the radiation pressure of photons on the mirrors forming an optical cavity causes the mirrors to move, thus exciting a mechanical vibration mode (Fig. 1). The mechanical motion, in turn, modifies the detuning of the incoming laser beam with the optical cavity resonance, hence altering the circulating beam. The dynamics of the field phase and amplitude inside the optical cavity are then nonlinearly coupled to the dynamics of the mirror position — the radiation pressure force being proportional to the field intensity. As has been popularized by Lorenz in the study of the so-called butterfly effect[2], any autonomous nonlinear system with at least three coupled state variables is a candidate for manifesting chaos, that is, unpredictable dynamics, the root of which is the deterministic sensitivity to the initial conditions.

In an optomechanical set-up (zoom-in on the optomechanical interaction in Fig. 1), it is known that a light beam that is blue-detuned with respect to the cavity resonance will release its energy to phonons at the frequency of the mechanical mode[3]. The light beam, therefore, self-amplifies the mechanical oscillations up to a point where the optomechanical oscillation overcomes the mechanical damping, hence resulting in an optomechanical oscillator. The transmitted light intensity is self-modulated at the frequency of the mechanical mode. When the intensity of the incoming light is further increased, the self-sustained oscillation bifurcates to more complex nonlinear dynamics including chaos[4].

Chaos is ubiquitous in nonlinear optical cavities, either resulting from nonlinear light–matter interaction[5,6] or from the nonlinear coupling between optical modes such as in laser cavities[7]. What makes optomechanical chaos peculiar, however, is the fact that the chaos is structural. Indeed, the self-oscillation frequency and chaos bandwidth can be adjusted by engineering the optical cavity and, more specifically, by engineering its corresponding mechanical and optical quality factors. Scalability and integrability of a large number of such optomechanical oscillators is therefore within reach for investigation of complex collective phenomena[8].

Writing in *Nature Photonics*, Faraz Monifi *et al.* report[9] that a single optomechanical oscillator can drive the transfer of optical chaos from a pump beam at one wavelength (1,550 nm) to another weaker probe beam at a different wavelength (980 nm). The physics, in brief, is the coupling of optical modes to the same mechanical mode in a microscopic toroidal optical cavity.

As shown in Fig. 1, two beams are coupled into and out of a microtoroidal resonator through a tapered optical fibre. The first beam (pump) is from an external cavity laser with a central wavelength of 1,550 nm and its power is increased to overcome the threshold