and has a very low absorption coefficient for NIR light. For example, NIR light (λ = 850 nm) needs to travel through just 0.14 μm of $In_{0.53}Ga_{0.47}As$ for half the photons to be absorbed compared with 13 μm for silicon. Thus, to create a conventional photodiode from silicon, the i region needs to be 100 times thicker, leading to a long drift transit time and hence much lower speed of operation.

So, is there a way that the speed of silicon diodes can be increased without compromising their efficiency? Gao and co-workers have come up with a photonic solution to this problem. By micropatterning a silicon p–i–n photodiode they were able to redirect normal incident light laterally along the plane of the photodiode. This thereby allowed them to maintain a thin intrinsic region in their photodiode with a high 'vertical' electric field and short drift-time (creating fast photodiodes) while also keeping the absorption, and hence efficiency, of their devices high. Thus, they avoid the compromise between speed and sensitivity by exploiting the larger lateral dimensions of the photodiode to increase the effective absorption of their device (Fig. 1).

There are a number of other methods to achieve silicon-integrated fast photodetectors. Silicon avalanche photodetectors (APDs) utilize a multiplication effect to achieve very high speed and up to single-photon sensitivity[3]. However, these devices typically require higher externally applied voltages than the devices described by Gao and colleagues. An alternate technology is metal–semiconductor–metal (MSM) photodiodes, which consist of interdigitated Schottky contacts on a silicon layer[5]. This MSM technology is highly compatible with CMOS technology, and is relatively high speed owing to low capacitance, however, the sensitivity is much lower than that of APD or p–i–n photodiodes.

So why bother with silicon if direct-gap semiconductors such as InGaAs can already provide us with high-speed, efficient photodiodes? The issue is with compatibility with integrated circuits that are dominated by silicon-based technologies, such as CMOS. Silicon photodiodes integrate well with other silicon-based components, even on single chips. On the other hand, Ge or InGaAs photodetectors are usually built as discrete components, or are combined with CMOS integrated circuits by wafer-bonding or flip-chip techniques that add expensive additional steps in the device fabrication process. However, alternative methods of direct growth of Ge on Si (ref. 6) or III–V nanowires on Si (ref. 7) could lead to more integrated competing technologies.

Probably the biggest drawback of silicon photodiode technologies for optical-fibre communications is the bandgap of silicon. Silicon's bandgap energy is 1.12 eV at room temperature, thereby limiting efficient photodiode operation to wavelengths <1,100 nm. Although 800–900 nm was originally used for optical-fibre communications, it is uncommon now for long-distance links owing to high attenuation of optical fibres at these wavelengths (~3 dB km^{-1} at 850 nm) and less-mature fibre amplifier technologies in this band as compared with low-dispersion 1,300 nm (O band) and low-loss 1,550 nm (C band) wavelength regions. The C band is most commonly used owing to excellent erbium-based fibre amplifiers and low attenuation (~0.2 dB km^{-1}). However, for shorter communication links, such as 'last mile' internet links, device-to-device connections or intranets, where cheap single-chip solutions are needed, sensitive and fast CMOS-integrated silicon photodiodes look most promising. ❐

Michael B. Johnston is in the Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK.
e-mail: michael.johnston@physics.ox.ac.uk

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METAMATERIALS

A low-energy Cherenkov glow

Hyperbolic metamaterials are shown to enable the emission of Cherenkov radiation from low-energy charged particles travelling at slow speeds. The achievement could lead to new forms of light sources and detectors.

Mário Silveirinha

It is well known that when fast charged particles travel inside a material with a speed exceeding the medium's phase velocity for light, they spontaneously emit electromagnetic radiation at the cost of a reduction in their kinetic energy. The effect is known as Cherenkov radiation and owes its name to Pavel Cherenkov — a Russian physicist who in the mid-1930s was a student working under Sergey Vavilov at the Lebedev Institute in Moscow and was studying the luminescence emitted from liquids under the incidence of highly energetic gamma rays[1]. This breakthrough earned him the Nobel Prize in Physics in 1958 alongside Ilya Frank and Igor Tamm, who helped explain the phenomenon. Often, the Cherenkov effect is associated with the blue glow of the water surrounding the core of nuclear reactors created by highly energetic beta particles released by the radioactive decay of nuclei. In fact, traditionally, the Cherenkov effect has various applications in the context of high-energy physics, for example, to detect cosmic ray events or in particle accelerators. Charged particles also emit radiation when they travel in a vacuum near a grating, an effect discovered by Smith and Purcell[2]. Furthermore, neutral polarizable atoms may spontaneously radiate away part of their kinetic energy when they travel near a smooth planar metal surface[3]. However, all of the above cited phenomena are generally relevant only when the particles travel with ultra-relativistic speeds.

Now, writing in *Nature Photonics*, Fang Liu and co-workers from

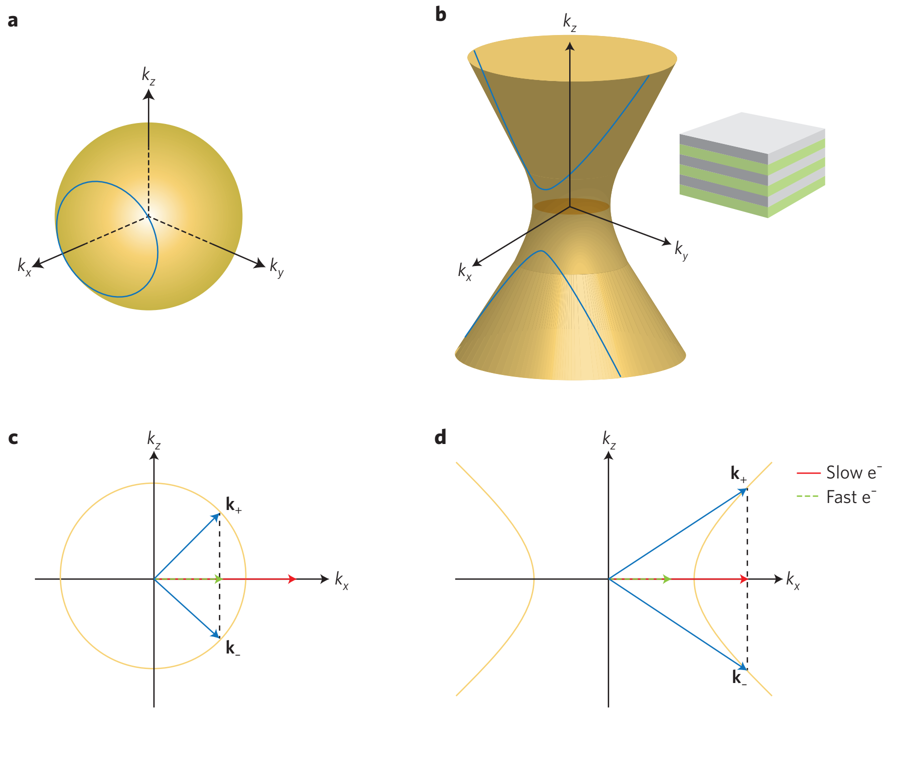

Figure 1 | Radiative channels for the Cherenkov effect. **a**, Generic spherical isofrequency surface (ω = constant) for a conventional isotropic material. **b**, Generic isofrequency surface for a layered hyperbolic metamaterial formed by a stack of gold and silica slabs (inset). **c**, Detail of the isofrequency contour of the isotropic material in the *x*–*z* plane. Very fast electrons (e^-) are associated with short transverse wavevectors (dashed green arrow) and can excite two photonic states $\mathbf{k}_+$ and $\mathbf{k}_-$ in the considered plane, and thereby emit Cherenkov radiation. In contrast, slow electrons (solid red, transverse wavevector) do not have available radiative channels. **d**, Similar to **c**, but for the hyperbolic metamaterial. The roles of the fast and slow electrons are reversed, and for a continuum it is possible to have Cherenkov emission with arbitrarily small velocities. In **a** and **b**, the blue contour (circle or hyperbola) represents the available radiative channels at frequency ω for some fixed electron velocity ($\mathbf{v} = v\hat{\mathbf{x}}$) for which there is Cherenkov emission.

Tsinghua University in China report the first on-chip integrated free-electron light source based on a hyperbolic metamaterial and the experimental demonstration of intense Cherenkov emission with low-energy electrons[4]. This effect has been previously theoretically predicted for a hyperbolic metamaterial formed by metallic nanowires[5]. Notably, because of the unique properties of the hyperbolic metamaterial and of its ultrahigh density of photonic states, the energy of the electrons involved can be as small as 250 eV, which corresponds to a velocity of $c/30$, where c is the speed of light in vacuum. This energy value is several orders of magnitude smaller than the energy necessary for significant Cherenkov emission to occur in natural materials. For example, the Cherenkov threshold energy in water is 261 keV (ref. 6).

In conventional isotropic dielectric media with negligible frequency dispersion, Cherenkov emission occurs when the velocity of the charged particles exceeds the threshold value: $v_{\text{th}} = c/n$, where $n = \sqrt{\varepsilon_r}$ is the refractive index of the material and ε_r is the dielectric constant of the material. For instance, to have Cherenkov emission with a velocity $v = c/30$ the dielectric constant of the medium needs to surpass $\varepsilon_r > 900$, which is a large and unusual value. For electron velocities $v < v_{\text{th}}$, radiative interactions are strictly forbidden and electrons may travel through the medium without losing energy. The reason for this constraint is that a photonic state with oscillation frequency ω and wavevector $\mathbf{k} = k_x\hat{\mathbf{x}} + k_y\hat{\mathbf{y}} + k_z\hat{\mathbf{z}}$ can only be excited by charges with velocity $\mathbf{v} = v\hat{\mathbf{x}}$ when the momentum-matching condition $k_x = \omega/v$ is satisfied. In conventional dielectrics, the wavevector lies in a spherical isofrequency surface, $k = n\omega/c$, with $k^2 = k_x^2 + k_y^2 + k_z^2$, and hence for small velocities no propagating states are accessible (Fig. 1a,c).

The key to unlock the radiative light–matter interactions with low electron energies is to tailor the form of isofrequency contours, such that the medium can support light states with extremely short wavelengths ($\lambda_m = 2\pi/k$) as compared with the light wavelength in vacuum, that is, states with a large value of k_x. Metamaterials — engineered media with nanoscopic features and unusual electromagnetic responses — provide the solution to the problem. Metamaterials are typically known for exotic wave phenomena, such as negative refraction, or for their applications in subwavelength microscopy[7]. Remarkably, artificial media — most notably hyperbolic media[8] and other materials with extreme anisotropy[5] — can also change fundamentally the manner in which charged particles interact with matter and thereby influence the occurrence of Cherenkov emission[5].

Hyperbolic metamaterials are uniaxial anisotropic structures characterized by a permittivity tensor $\bar{\varepsilon} = \varepsilon_{||}(\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{y}}\hat{\mathbf{y}}) + \varepsilon_{zz}\hat{\mathbf{z}}\hat{\mathbf{z}}$, such that the signs of the permittivity components along the optical axes are opposite $\varepsilon_{||}\varepsilon_{zz} < 0$ (ref. 8). For a fixed frequency, the photonic states supported by a hyperbolic medium lie in a hyperbola (Fig. 1b) determined by

$$\frac{k_x^2 + k_y^2}{\varepsilon_{zz}} + \frac{k_z^2}{\varepsilon_{||}} = \left(\frac{\omega}{c}\right)^2$$

in sharp contrast with conventional dielectrics for which the photonic states lie in a spherical surface (Fig. 1a). Evidently, in a hyperbolic medium the isofrequency surfaces are unbounded. Notably, this means that for a fixed ω, a hyperbolic medium may support states with arbitrarily short wavelengths, and thus, for a sufficiently small velocity, there are always available radiative channels that satisfy the momentum-matching condition (Fig. 1d).

Liu and colleagues' hyperbolic metamaterial is simply a stack of gold and silica layers. For such a design it is reasonable to assume that ε_{zz} is approximately independent of frequency and is positive whereas $\varepsilon_{||} = \varepsilon_{||}(\omega)$ is negative in a broad spectral region. In this case, it can be theoretically shown that radiative channels are available when $v < c/\sqrt{\varepsilon_{zz}}$ (ref. 4). Thus, in contrast with conventional natural media, for emission to take place the electron velocity needs to be below a maximum value rather than above a minimum value. Indeed, in the limit wherein the hyperbolic metamaterial is regarded as a continuum the Cherenkov emission has no minimum velocity threshold[4,5]. Radiation emission with no velocity threshold is also possible in photonic crystals[9] and in gratings[2,10], but it is typically weaker due to the increased selectivity in frequency. More generally, metamaterials can modify in unique ways the radiation emitted by fast charged particles, and enable interesting phenomena such as the generation of reversed Cherenkov cones[7,9,11] and collimated emission[5,12].

The on-chip light source reported by Liu *et al.*[4] has an integrated planar electron gun, so that the emitted electrons fly in a vacuum at a distance as small as d = 40 nm atop the metamaterial structure. Thus, in practice, the distance d provides a natural cut-off for the wavevector, as states with $|k_x| > 1/d$ are weakly excited. Furthermore, the effective medium approximation breaks down for wavelengths comparable to or shorter than the characteristic period a of the metamaterial. Indeed, the granularity of the metamaterial cannot be ignored for waves with $|k_x| > 1/a$ (refs 5,13). This means that while in an ideal hyperbolic continuum the emitted Cherenkov radiation has no velocity threshold, in a realistic structure the velocity of the electrons always needs to surpass some minimum value. Strikingly, in Liu and colleagues' design, this threshold velocity is estimated to be as low as $c/200$.

The exceptionally large Cherenkov emission described by Liu *et al.* is made possible by an ultra-large density of photonic states with short wavelengths[5,13]. Remarkably, in the continuum limit, the density of photonic states that satisfy the momentum-matching condition is divergent because the intersection of the plane $k_x = \omega/v$ with the isofrequency surface yields a curve (blue hyperbola in Fig. 1b) with infinite length. In addition, the response of hyperbolic metamaterials is typically broadband, and due to this reason the available radiative channels populate uniformly a large portion of the electromagnetic spectrum. Liu *et al.* report that in their experiment the emitted spectrum covers the spectral range 500 nm < λ_0 < 900 nm, peaking at the free-space wavelength 700 nm.

Despite Liu and co-workers' impressive results, a few challenges lie ahead. The first is that the electron gun needs to be placed in a vacuum chamber so that the flying electrons are not stopped by collisions with air molecules. It will be interesting to see if in the future this constraint can be overcome and if the technology can be made fully on-chip either by using an on-chip vacuum chamber, or perhaps with a solid-state material that supports the ballistic transport of electrons[14]. The second hurdle is that most of the Cherenkov radiation emitted actually remains within the metamaterial. Owing to the extremely short wavelengths involved, it is not simple to efficiently extract the emitted radiation and to use it to illuminate an object in the far-field as is the case with a conventional laser device. Despite this difficulty, Liu *et al.* report that by using a resonant grating to outcouple the light, the power extracted from the metamaterial can exceed by two to three orders of magnitude the power that is obtained with more conventional structures. The experimental verification of broadband Cherenkov emission with such low-energy electrons is likely to open exciting new avenues in nanotechnologies, and it is easy to imagine that it will find applications in the context of particle detection, nanoscale light sources, or biomedicine[6]. ❐

Mário Silveirinha is at the University of Lisbon–Instituto Superior Técnico and Instituto de Telecomunicações, Avenida Rovisco Pais, 1, 1049-001 Lisboa, Portugal.
e-mail: mario.silveirinha@co.it.pt

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VIEW FROM... JSAP SPRING MEETING

A marriage of materials and optics

A laser-annealing technique for increasing the dopant concentration in semiconductors, the creation of a glass with second-order optical nonlinearity and the realization of optical topological insulators were highlights at the Japan Society of Applied Physics Spring Meeting.

Noriaki Horiuchi

The interplay between optical science and novel materials, and how research into one can aid the other and vice versa, was strongly apparent at the recent 64th Japan Society of Applied Physics (JSAP) Spring Meeting. Held at Pacifico Yokohama, Japan, on 14–17 March, 7, 114 scientists from academia and industry gathered and there were 4,046 oral and poster presentations. Here are a few highlights that caught our attention.

Metal-oxide–semiconductor field-effect transistors based on GeSn are promising for realizing integrated circuits with low power consumption. However, it has been technically difficult to create n-doped GeSn polycrystals. To date, the maximum concentration of Sb — an n-type dopant — that has been added to a $Ge_{1-x}Sn_x$ polycrystal is on the order of 1.7×10^{19} cm^{-3} by flash lamp annealing.

At the meeting, Kouta Takahashi from Nagoya University reported that he has succeeded in increasing this value by about a factor of four to 6.7×10^{19} cm^{-3} by using pulsed laser annealing in water. A proof-of-principle experiment was demonstrated using KrF excimer laser irradiation (wavelength of 248 nm and pulse width of 55 ns) and amorphous $Ge_{1-x}Sn_x$:Sb in water. "Melting and recrystallization