News & views

Photonics

Electrons flip a switch on optical communications

Satoshi Hiura

Clever manipulation of electrons has enabled scientists to change a key property of light emitted by a device using electrically controlled magnetization. The method could lead to stable and energy-efficient information transfer. **See p.783**

Advances in information technology have a tremendous impact on people's lives, but they come with massive increases in the power required to store, process and transmit huge amounts of data[1]. This issue can be remedied by encoding information not only in the charge of electrons, as is the case for conventional electronics, but also in electrons' intrinsic angular momentum (spin), through a branch of electronics known as spintronics. Spintronic computer memories are expected to replace existing memories, but the information encoded in spin is transmitted most efficiently with light, which requires optimization of yet another technology, called photonics. On page 783, Dainone *et al.*[2] have manipulated light by electrically controlling the magnetization of a material, paving the way for efficient information technologies that seamlessly integrate electronics, spintronics and photonics.

Modern ultrafast optical communication usually involves transmitting information by storing it in the adjustable intensity of laser light – a process that is much faster than conventional electronics, but has inherent physical limits. Another approach uses circularly polarized light, which has an electromagnetic field that rotates in a plane perpendicular to the direction of its motion. This means that information that is encoded in the orientation of electron spins (which can be either up or down) can be transferred to left-polarized or right-polarized photons, because the angular momentum of the photons couples to the spin. Changing between polarization states is predicted[3] to be much quicker than switching between intensity levels, and a laser based on this principle already operates ten times faster than an intensity-modulated laser[4].

Circular polarization can be controlled electrically in a device that uses an alternating current flowing between two electrodes to switch between polarization states[5], but the alternating current complicates the set-up. Dainone *et al.* took a different approach, in which electrons were injected from a single source into a layer comprising tiny crystals called quantum dots. This layer was embedded in a semiconductor material through which electrons and holes (their positively charged counterparts) could flow (Fig. 1). The quantum dots emitted light when an electron interacted with a hole, and the spin of the electron determined the handedness of the light emitted (the direction in which its electromagnetic field rotated).

Dainone *et al.* controlled the orientation of the spins through a phenomenon known as magnetization switching, which was induced by a material property called spin–orbit torque[6]. The channel through which the electrons were injected consisted of a ferromagnet (a common bar magnet) connected to a heavy metal. When the authors pulsed an electrical current through the channel, a property of the heavy metal, known as spin–orbit coupling, made electrons with opposite spins move in opposite directions, perpendicular to that of the current. The orientation of these spins was misaligned with the magnetization of the ferromagnet, and this led to a torque being exerted on this magnetization, switching its direction. Changing the direction of the current reversed the magnetization in the opposite direction.

The authors' injector channel was made up of a stack of ultrathin layers of magnesium oxide, cobalt iron boron, tantalum and chromium. The addition of chromium improved

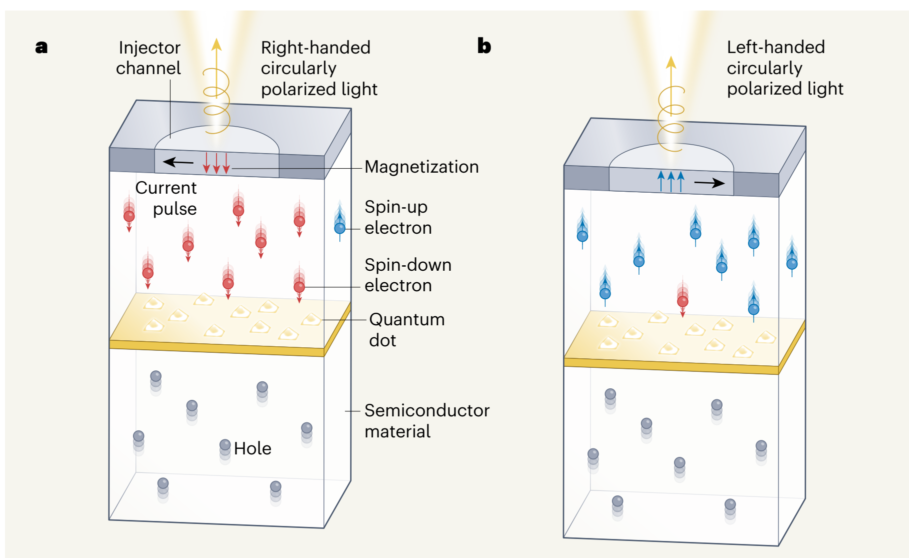

Figure 1 | Switching the polarization of light. Tiny crystals called quantum dots can emit light when an electron interacts with a hole (an electron's positive counterpart). Dainone *et al.*[2] have developed a clever way of switching the emitted light's circular polarization (the direction in which its electromagnetic field rotates; either right or left), which is coupled to the intrinsic angular momentum (spin) of the electron (either up or down). **a**, The authors embedded a layer of quantum dots in a semiconductor material, and injected electrons into this material through a channel that was designed to control the orientation of the electrons' spin. A current pulse separated electrons with opposite spins, and this had the effect of switching the magnetization of the channel, thereby polarizing the spins of the injected electrons. **b**, Changing the direction of the current reversed the magnetization and thus the spin polarization of the injected electrons. (Adapted from Fig. 1c of ref. 2.)

the magnetization switching, and reduced the electrical resistance of the channel, resulting in a considerable increase in the maximum current that could be applied before the device broke down. Indeed, Dainone *et al.* found that omitting this layer caused some damage to the ferromagnet–semiconductor interface, owing to the effect of the current pulse. The other layers have a property known as perpendicular magnetic anisotropy, which is essential for maintaining the up and down spin states of the electrons in the absence of an external magnetic field.

By placing the injector channel as close as possible to the quantum-dot layer, Dainone *et al.* ensured that the spin polarization of the electrons would be kept high as they moved through the semiconductor. This allowed the authors to achieve a high degree of circular polarization: switching the magnetization effected a change from 31% of photons being left-polarized to 31% of them being right-polarized. That the authors could accomplish this without needing to apply an external magnetic field makes the approach both practical and promising.

Dainone and colleagues found that they could generate light with intermediate polarization by using the current pulse to obtain intermediate magnetic states in the ferromagnet. Through precise control of the magnetization switching, they were able to establish multistate circular polarization. This is key to the applicability of the approach because it suggests that multilevel modulation will be possible for polarization-based optical communications, just as it is for intensity-based approaches.

The speed of polarization switching in the authors' device depended on the speed of magnetization, which, in turn, relied on the duration of the current pulse through the injector channel. The shorter the duration of the pulse, the larger the current required to switch the magnetization. Dainone *et al.* achieved a minimum pulse duration of 1 millisecond, but they predict that this could be shortened by changing the type of heavy metal in the spin injector.

Some other challenges remain. The authors used a single layer of quantum dots, but several layers would be better for maximizing the amplification of the light intensity. However, this would increase the distance between the injector channel and the extra light-emitting layers, and would thus reduce the spin polarization of the electrons injected into these layers. To incorporate quantum-dot multilayers, the authors therefore need to develop a spacer material that can suppress the electrons' tendency to become unpolarized as they move through the semiconductor.

The extent to which the light emitted is circularly polarized could also be increased by incorporating different materials into the injector channel. For example, the spin polarization of the electrons injected into the semiconductor would be enhanced by a material that has half-metallic properties (that is, a spin polarization of 100%) as well as perpendicular magnetic anisotropy. At room temperature, electron spin polarization decreases rapidly in gallium arsenide, the semiconductor material that the authors used. This problem might be solved by using dilute nitride gallium arsenide instead, because the defects introduced by nitrogen can have a 'spin-filtering' effect[7]. Even without these improvements, Dainone and colleagues' work presents an exciting glimpse of a way to achieve superior information technologies at little cost to the environment.

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1. Jones, N. *Nature* **561**, 163–166 (2018).
2. Dainone, P. A. *et al. Nature* **627**, 783–788 (2024).
3. Faria, P. E. Jr *et al. Phys. Rev. B* **92**, 075311 (2015).
4. Lindemann, M. *et al. Nature* **568**, 212–215 (2019).
5. Nishizawa, N., Nishibayashi, K. & Munekata, H. *Appl. Phys. Lett.* **104**, 111102 (2014).
6. Chernyshov, A. *et al. Nature Phys.* **5**, 656–659 (2009).
7. Huang, Y. *et al. Nature Photon.* **15**, 475–482 (2021).

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In retrospect

50 years after a landmark paper on bird-flight origins

Kevin Padian

For a century, scientists pondered whether bird flight evolved by animals gliding down from trees or by creatures running and flapping from the ground up. A landmark 1974 paper reset the debate to focus on the evolution of the flight stroke instead.

One could speculate about how birds evolved flight without knowing what ancestors they evolved from, or with no information on the specifics of their body form, ecology or behaviour. And that had been exactly the state of the debate among palaeontologists and ornithologists since the issue was first broached in the 1870s, using imaginary ancestries, imaginary life histories and imaginary aerodynamics. In 1974, writing in the *Quarterly Review of Biology*, the palaeontologist John Ostrom[1] approached the conundrum using evidence from both the fossil record and the behaviour of living animals. And he effectively turned the debate on its head.

Why was the question of the origin of bird flight so difficult to solve? Consider the problem of evidence. Birds had to have come from forerunners, which had always been assumed to be reptiles rather than mammals. But the fossil record was incomplete between some major adaptive transitions (such as from ground- or tree-dwelling reptiles to flying birds), and potentially ancestral fossil reptile groups always seemed to have some but not all of the expected ancestral features, or to have them in the wrong combinations.

Between 1973 and 1976, Ostrom, working at Yale University in New Haven, Connecticut, published a series of papers[1–4] that proposed that birds evolved from small theropod (carnivorous) dinosaurs, and that bird flight evolved from the ground up, not from the trees down. He had assiduously studied *Archaeopteryx* – the earliest known bird and perhaps the world's most famous fossil species – of which 4 specimens were available at that time (there are now 12). His interest was piqued because, only a few years earlier, he had fully described the small theropod dinosaur *Deinonychus* (the model for raptors in the 1993 film *Jurassic Park*) from fossils found in Montana that dated to the early Cretaceous period (around 100 million to 110 million years ago)[5]. He was amazed by the extensive suite of similarities between theropod dinosaurs and *Archaeopteryx*[3,4].

For a century before Ostrom's work, palaeontologists had considered a variety of fossil reptile lineages, all at least as old as the late Triassic (roughly 225 million years ago), as possible bird ancestors. The default hypothesis was that birds evolved from a poorly defined group of creatures called thecodonts (a ragtag bunch related variably to crocodiles or dinosaurs), from a crocodile lineage or possibly from dinosaurs (ornithischians or saurischians)[3]. Responding to an argument raised by the British palaeontologist Alick Walker that birds evolved from a hypothetical