of energy levels of one erbium atom with nuclear spin 7/2. Remarkably, the laser light used in the set-up did not cause excessive charge noise in the SET. Although the nuclear spin state was detected using multiple laser shots, single-shot detection and manipulation of single nuclear spins should become possible with further refinements of the technique.

These results are a major step towards access to both single spins and photons in a silicon-based platform — a combination that might be used to attain efficient quantum communication. The findings are also exciting because they expand the list of atoms and atomic defects for which reliable single-spin access can be obtained, beyond phosphorus in silicon[3] and nitrogen-vacancy centres in diamond[5]. And, as Yin *et al.* point out, other atomic defects can be probed with this method, too. Compared with the popular optical methods for measuring the spins of nitrogen-vacancy centres, which can be performed at room temperature, the authors' hybrid optoelectronic approach circumvents the problem of limited photon-collection efficiency that plagues purely optical methods.

It is also noteworthy that the SET used here is a FinFET[6], a three-dimensional type of transistor that is mass-produced for processors in consumer electronics. Devices based on the authors' hybrid approach might therefore serve as a platform for expanding the functionality of semiconductor systems beyond the mere shuffling of electrons to encode 'zeros' and 'ones' — the classical bits of digital information and computing. With regard to quantum computing, which requires integration of quantum memory, logic and communication modules, Yin and colleagues' work offers a promising route towards the integration of spin- and photon-based quantum bits (qubits) in silicon. This is because nuclear spins of dopant atoms such as erbium and phosphorus have extremely long 'coherence times', which are desirable for quantum memories[7]. In addition, quantum information could be transferred between electron and nuclear spins[8] and possibly also encoded in single photons emitted by an erbium atom.

To integrate erbium-based qubits into a photonic network, the issue of efficient photon collection will also have to be addressed, perhaps by placing the qubits in optical cavities (arrangements of highly reflective mirrors that trap light). And although many challenges remain, integrating these elements in silicon has the tantalizing potential to achieve distributed quantum-computing architectures (see, for example, ref. 9) at the exact wavelength that is used for classical telecommunication. ■

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OPTICAL DEVICES

Seeing the world through an insect's eyes

An elegant combination of electronics and elastic materials has been used to construct a small visual sensor that closely resembles an insect's eye. The device paves the way for autonomous navigation of tiny aerial vehicles. SEE LETTER P.95

ALEXANDER BORST & JOHANNES PLETT

Flies are usually treated with disdain. Most commonly associated with spreading disease, they are at best considered simply annoying. Conversely, and far less appreciated, flies have also inspired mankind for centuries. An early report along these lines dates back to the seventeenth century, when the young René Descartes, while lying sick in bed, observed a fly walking along the ceiling of his room. Thinking about how he could describe the path of the fly in quantitative terms, he came up with what has become known as Cartesian coordinates, which allow algebra to be applied to geometry, and the importance of which can hardly be overestimated. The most recent example of such insect-inspired research is described by Rogers and colleagues (Song *et al.*[1]) on page 95 of this issue — the authors have transferred the design of an insect's compound eye to a digital camera.

In almost all cameras used today, the light reflected from an object in the environment is collected by a single lens and projected onto a layer of light-sensitive material in such a way that a sharp image is formed. Our eyes, as well as all other vertebrate eyes, also use this principle of image formation. The concept has the clear advantage of optimal usage of photons, guaranteeing maximum light sensitivity. Furthermore, it provides high spatial resolution, which is limited only by the density of photoreceptors in the focal plane of the lens.

Nevertheless, most living organisms use compound, or faceted, eyes instead of lensed eyes to see the world. Faceted eyes have very different optics and are composed of many hundreds or thousands of optical units (facets)[2]. In the case of the 'apposition' eye of daylight insects, each facet is optically isolated from its neighbour and equipped with its own

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Figure 1 | Insect-inspired visual sensor. Song *et al.*[1] have designed a visual sensor that resembles, both functionally and structurally, the apposition eye of a daylight insect.

lens and set of photoreceptors. Because each facet accepts photons from only a small angle in space, the light sensitivity of apposition eyes is rather low and the spatial resolution is limited by the number of facets that can be packed on to the small head of the insect. However, apposition eyes provide their bearer with a panoramic view of the world as well as with an infinite depth of field, without the need to adjust the focal length of the individual lenses.

Song and colleagues now report the successful engineering of a digital camera that mimics the insect apposition eye in almost every aspect (Fig. 1). To achieve this end, the authors combined an array of elastic microlenses and a deformable array of photodetectors into a two-layer design, and transformed both layers from a planar geometry into a hemispheric shape (see Fig. 1 of the paper[1]).

The key to the success of this procedure lies in maintaining correct alignment between both sheets so as not to introduce unwanted optical artefacts. Song *et al.* attained this by

rigidly joining the two layers only at the precise locations where the microlenses overlie the photodetectors, while permitting the layers to deform independently elsewhere. The use of a turret-like, domed structure for each microlens effectively decoupled the microlenses from the mechanical stress caused by bending. Furthermore, the authors used deformable, serpentine conductor wires as a flexible electrical interconnect between photodetectors. The result is a small, artificial faceted eye with a near-hemispheric field of view, without off-axis aberration and with an almost infinite depth of field.

Given their almost complete coverage of visual space, faceted eyes are ideal for calculating the apparent motion of an object generated by its motion relative to the observer (optical flow)[3]. With regard to potential applications, the camera proposed by Song *et al.* might constitute an optimal front-end visual sensor for tiny aircraft called micro aerial vehicles (MAVs)[4]. Although, so far, most cameras on board MAVs simply use fisheye lenses to produce a wide-angle field of view[5], Song and colleagues' camera would provide all the advantages of an apposition eye. Using it to compute a MAV's self-motion could on the one hand facilitate motion stabilization in space while on the other enabling spatial navigation[6].

As with any development, there is always room for improvement. The camera's low light sensitivity, which is inherent in apposition eyes, could be ameliorated by placing more than one photodetector beneath each microlens and combining the output of photodetectors in neighbouring facets looking at the same point in space. In fact, flies use this principle of 'neural superposition' to increase the amount of light detected by the eye by a factor of seven, thereby achieving significantly higher light sensitivities[7].

Such resolvable issues aside, the system proposed by the authors could prove a stepping stone towards autonomous navigation of MAVs in their manifold possible uses. One major application is disaster relief. Picture the following: a palm-sized MAV uses an artificial faceted eye to navigate autonomously through a collapsed building while other sensors on board scan the environment for smoke, radioactivity or even people trapped beneath rubble and debris. Although these MAVs do not exist yet, thanks to devices such as that reported by Song *et al.*, they should come within reach in the foreseeable future. ■

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MOLECULAR BIOLOGY

The ends justify the means

A genomic analysis of yeast reveals that individual genes produce a rich complexity of RNA molecules with differing start and end sequences. The variation in these transcripts reflects the diversity of gene-regulation mechanisms. SEE LETTER P.127

B. FRANKLIN PUGH

It seemed simple enough, the idea that one gene encodes one RNA transcript that is translated into one protein. But over the past 50 years, molecular biology has proven to be more complex than this 'central dogma', first proposed by Francis Crick in 1958[1]. On page 127 of this issue, Pelechano *et al.*[2] take transcript complexity to new ends, reporting nearly 2 million different RNA transcripts for a yeast genome that contains roughly 6,000 protein-encoding genes*.

The RNA molecules studied by the authors are called transcript-RNA isoforms, or TIFs. These are RNAs that traverse the same region of a genome, but have differing start (5′) and end (3′) sequences. Different TIFs have the potential to alter the coding and regulatory capacity of RNA[3,4], and so the diversity of TIFs identified is intriguing. However, the plethora of isoforms may distil down to a relatively small number of functionally distinct RNAs for each gene (Fig. 1). For example, the TIFs found by the authors often have ends just a few nucleotides apart, and can be clustered into about 370,000 major TIFs (mTIFs). TIFs belonging to an mTIF probably arise from imprecise initiation of transcription. Moreover, isoforms can be quite rare compared with the predominant TIFs, which raises questions about the importance of low-abundance TIFs. The advance presented by Pelechano and colleagues' study is the comprehensiveness and resolution of TIF identification, and the complexity of transcript diversity, that can be revealed by sequencing both the 5′ and 3′ ends of the same RNA molecule.

When piecing together the full complement of RNA transcripts in a cell from sequencing data, one may be erroneously led into thinking that two overlapping transcripts represent a single longer transcript, such that distinct transcripts might go unnoticed. This problem is exacerbated by the fact that some sequencing methods fall short of reading both ends of the same RNA molecule, owing to very long transcript lengths and short-read technology. This problem was solved by methods that generate paired-end ditags (PETs)[5], in which the 5′ and 3′ ends of an RNA molecule are converted to DNA and stitched together; sequencing across this junction allows simultaneous identification of both ends of the RNA. Pelechano *et al.* present a refined version of this method, called TIF-Seq, which they use in conjunction with deep sequencing, such that each RNA sequence is detected multiple times in the data set.

A typical protein-coding messenger RNA (mRNA) molecule has three main parts: a 5′ untranslated region (UTR), a coding region (also called an open reading frame, or ORF) and a 3′ UTR. Pelechano and colleagues' analysis shows that all of these regions can be varied in a cell's TIF repertoire, and suggests how this might regulate cell function. For example, the authors identify more than 200 genes with mTIFs that start or end within the coding region, thereby resulting in truncated proteins with potentially altered function. UTRs often contain regulatory elements that alter mRNA stability and protein-translation efficiency, and the authors also find that these regulatory elements occur more often where the location of 5′ and 3′ ends is most variable. Thus, by virtue of where the enzyme RNA polymerase II, which transcribes DNA to RNA, starts or stops, the resulting RNA may have a vastly different rate of turnover or translation.

The authors also report more than 700 examples of differential UTR usage that is related to the presence of an upstream ORF (uORF). uORFs are thought to be too short to code for a protein, but they may regulate the translation frequency of the downstream ORF, thereby affecting the amount of protein produced. However, the TIF-Seq assay revealed that about half of the annotated uORFs are actually transcribed independently of the downstream ORF, suggesting that they have

*This article and the paper under discussion[2] were published online on 24 April 2013.