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DEVICE PHYSICS:

Toward Efficient Smart Pixels

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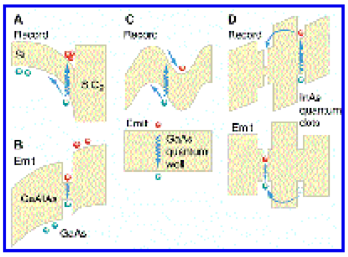
Much of information technology revolves around the analysis, storage, and processing of visual images and patterns. Usually an image is recorded with a charge-coupled device (CCD) camera in the form of pixels, that is, points of varying color and intensity, thus converting the image into a series of digital electronic signals. These are stored and processed by a computer, often transmitted through fiber optic networks, and finally converted back into visual images on a display consisting of light-emitting diodes (LEDs). A more direct way of image processing uses so-called smart pixels (1, 2): arrays of active devices fabricated on the same chip that operate in parallel to detect, process, and emit photonic signals. By combining the world of image detection and processing with that of electronics on a single chip, smart pixels have the potential to process visual images more efficiently than present technologies.

Today's smart pixels are rather complex, and their image resolution cannot match that of a CCD camera. But a clever device reported by Lundstrom *et al.* (3) on page 2312 of this issue may help to make smart pixels more competitive. The device detects light pulses through photogenerated charges, stores its intensity information for up to seconds, and reemits it again as a light pulse. Such a storage device for photonic signals might be developed into a smart pixel that can easily be fabricated in large numbers on a single chip.



Processing of photonic signals in semiconductor devices. In a CCD camera (**A**), photons (blue arrows) excite electrons (red) across the band gap (yellow) of silicon that are trapped at the Si-SiO_2 interface. In an LED (**B**), a photon is generated when a conduction band electron recombines with a valence band hole (green). Reversible storage of photogenerated electron-hole pairs becomes possible in devices that spatially separate the electron and hole by trapping each of them either in an electrostatically deformed quantum well (**C**) or a pair of quantum dots tilted by an electrostatic seesaw (**D**) that can be switched to induce fast recombination.

The device aims to combine the sensitivity of a CCD camera with the efficient emission of an LED in a single device. It relies on controlling the lifetime of light-generated electron-hole pairs by spatially separating them in a reversible manner (4-6). In a CCD camera (see panel A in the figure), an individual photon lifts an electron from an occupied state in the silicon across an energy gap into the conduction band, leaving behind a positively charged empty state called a hole. Strong electric potential gradients generated by external electrodes spatially separate the electron from this hole and trap it in a potential pocket at the Si-SiO_2 interface. Such potential pockets generated by time-dependent voltages can accumulate many photogenerated electrons and move them like a conveyor belt (5) to the outside circuit. The astonishing recording sensitivity of a CCD camera is a result of the rather long natural lifetime of a photoexcited electron-hole pair in silicon, which allows efficient electron trapping. The opposite happens in an LED (see panel B in the figure): Electrons and holes are injected from different contacts into the active region of a suitable semiconductor, where they quickly recombine, emitting photons with band gap energy. This is very efficient if one traps the electron and hole in a narrow quantum well of a material such as gallium arsenide (GaAs), with short radiative recombination lifetimes of typically 10^{-9} s.

Lundstrom *et al* . trick nature by developing an efficient handle on the recombination lifetime of an electron-hole pair. Previous schemes to control recombination have spatially separated and trapped both electrons and holes in tilted double quantum wells (4), in the piezoelectric potential pockets of a surface acoustic wave travelling along a quantum well (5), or in potential pockets of a quantum well created electrostatically by small electrodes (6) (see panel C of the figure). These devices can store photogenerated electron-hole pairs for tens of microseconds, more than four orders of magnitude longer than their natural lifetime. Lundstrom *et al.* combine coupled quantum dots with a tiny electrostatic seesaw to trap photogenerated electron-hole pairs in fully confining cages (see panel D in the figure), increasing their storage time to seconds at low temperature before photon emission is induced.

Such devices may potentially be fabricated into large pixel arrays capable of high-resolution image processing. However, quite a few obstacles must be overcome before this intriguingly simple concept becomes a useful and competitive device. Reversible and effective storage of electron-hole pairs at room temperature remains to be demonstrated; similar to a CCD, this appears to be essentially a matter of proper choice and cleanliness of materials. Long storage time as realized by Lundstrom *et al* . in enclosing electron and holes in the cages of quantum dots should ideally be combined with fast and efficient release of photons. Here, the electrostatic devices (see panel C of the figure) appear to have an advantage over the seesaw-like devices (see panel D of the figure), because they do not need fast tunneling of carriers for both the recording and the emitting mode. A third problem is how to efficiently reemit the radiation into a preferential direction. Here the combination of electron-hole pair storage with the already well-established concepts of optical microcavities (7) and photonic band gap structures (8) appears to be the most promising route to a solution.

Most likely it will still take several years to transfer the elegant concept of reversible storage of photogenerated electron-hole pairs into practical photonic processing devices. At present, one can only speculate whether such devices will eventually be able to compete with conventional digital image processing or other smart pixel arrays. But the potential of doing so makes them an attractive subject for further investigations and improvements.

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