ONTOLOGY:
Physical sciences / Optics and photonics / Applied optics / Optoelectronic devices and components [URI /639/624/1075/401]
Physical sciences / Optics and photonics / Applied optics / Optical sensors
[URI /639/624/1075/1083]

SUBJECT: Optoelectronics

TITLE: Fast Silicon Photodiodes

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How much internet traffic did you generate today? Perhaps more than you realise given the increasing popularity of streaming audio or video content, “cloud” data storage, and social media. It is estimated that approximately 1 zettabyte (10^{21} bytes) of internet traffic was transmitted globally last year,[1] which is the equivalent of about 360MB per day per person in the world. Much of the long distance, high volume internet traffic is transmitted via near infrared (NIR) light through optical fibre waveguides. At the end of the optical fibre the optical signal is turned into an electrical signal, typically for use in silicon based integrated circuits. However, presently most receivers for long distance optical fibre communications systems are based on photodiodes made from other semiconductors such as $In_xGa_{1-x}As$, or Ge which are challenging and costly to integrate with silicon CMOS electronics on a single chip.

Now writing in Nature Photonics, Gao and co-workers report on a silicon photodiode which utilises photonic micro-structuring to develop a photodiode that is both fast and responsive.[2] As their technology is naturally compatible with current silicon CMOS technology this work could lead to cheaper and better integrated fibre optic communications systems.

Fibre optics is an excellent technology for transmitting large volumes of information. The good news is that we are at present only exploiting a small fraction of the available bandwidth of light (~200THz for NIR light) in our communication systems. However, in order the increase the density of information transfer we need to continually develop technologies to modulate the light at higher frequencies, control dispersion in the optical fibres and be able to detect shorter and shorter pulses of light. [3]

The purpose of a photodiode is to turn an optical signal into an electrical one. The electrical current generated by an ideal photodiode illuminated with light of a particular wavelength is directly proportional to the number of photons hitting the device per second. The more closely the electrical signal can follow changes in the intensity of light the ‘faster’ the photodiode. This speed or response time of a diode is important as the faster the photodiode diode, the more closely spaced in time the 1s and 0s (ie ons and offs) of a digital signal can be, and hence the faster information can be transmitted.

So what limits the 'speed' of a photodiode? Consider the operation of a conventional "p-i-n" photodiode which consists of a sandwich of thin *p*-doped, *i*ntrinsic and *n*-doped layers of semiconductors. Light is absorbed according to Beer's law though the p, i and n layers. The transit of photons through the device and generation of electron-hole pairs occurs on a femtosecond timescale and this does not limit the photodiode speed. Instead, it is the collection of the photo-generated electrons and holes that determines the speed of the diode. In the case of a p-i-n diode speed is typically limited by (i) diffusion of photo-generated electrons and holes to the high electric field 'depletion region' of the device, (ii) the 'drift' transit time of electrons and holes under the influence of the electric field in the depletion region and (iii) the capacitance of the device. [4]

In order to minimise the effect of slow diffusion effects, most light should be absorbed in the high electric field *i* layer, rather than in the *n* and *p* layers. While to minimise the drift time and achieve low voltage operation the *i* region should be thin. Efficient and high-speed photodiodes can be achieved quite well with direct-bandgap semiconductors such as InGaAs, which have very high absorption coefficients for NIR light. However, silicon is an indirect bandgap semiconductor and has a very low absorption coefficient for NIR light. For example NIR light (lambda =850nm) needs to travel though just 0.14μm of $In_{0.53}Ga_{0.47}As$ for half the photons to be absorbed compared with 13μm for silicon. Thus, to create a conventional photodiode from silicon the *i* region needs to 100 times thicker leading to a long drift transit time and hence much lower speed operation.

So, is there a way that the speed of silicon diodes can be increased without compromising on their efficiency? Gao and co-workers[2] have come up with a photonic solution to this problem. By micro-patterning 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 (as illustrated in Figure 1).

There are a number of other methods to achieve silicon-integrated fast photodetectors. Silicon avalanche photodetectors (APDs) utilise 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 et al. 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 other electronics which is 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 which add expensive additional steps in the device fabrication process. However alternative methods of direct growth of Ge on Si [6] or III-V nanowires on silicon [7] could lead to more integrated completing technologies.

Probably the biggest drawback of silicon photodiode technologies for optical fibre communications is the bandgap of silicon which is 1.12eV at room temperature which limits efficient photodiode operation to wavelengths < 1100nm. Although 800-900nm 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 (~3dB/km at 850nm) and less mature fibre amplifier technologies in this band as compared with low dispersion 1300nm (O band) and low loss 1550nm (C band) wavelength regions. The C band is most commonly used owing to excellent Er based fibre amplifiers and low attenuation (~0.2dB/km at 1550nm). 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.

References:

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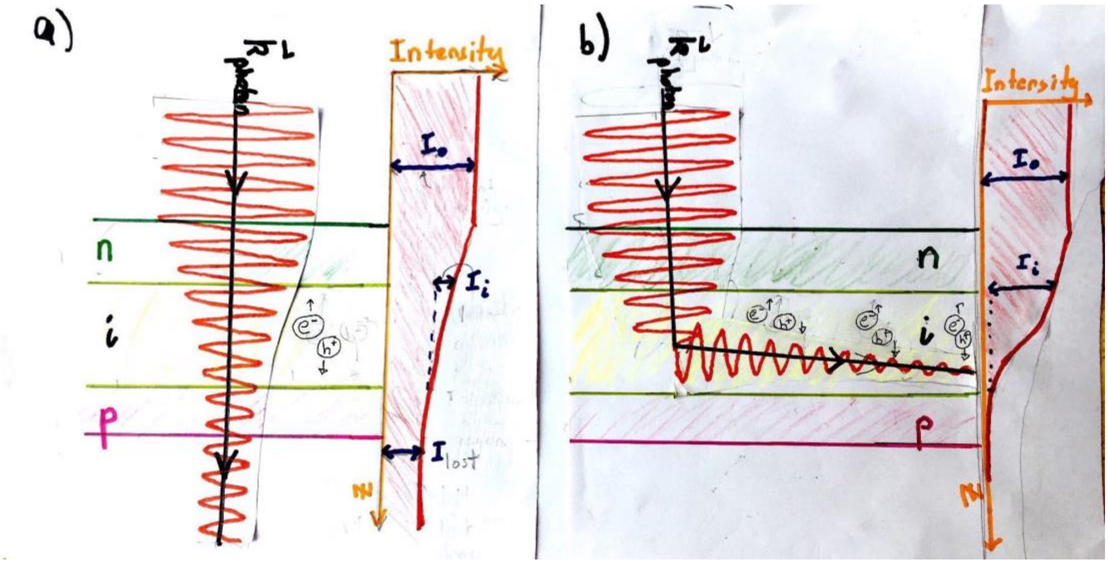

Figure Caption:

Stylised diagram showing propagation of light with intensity I_0 and wavevector $\mathbf{k}_{\text{photon}}$ incident normal to the surface of a p-i-n photodiode. Absorption of photons in the high electric-field i-region of the device leads to electron (e-) and hole (h+) pair production which rapidly contribute to photocurrent. (a) For propagation straight through a conventional thin device only I_i/I_0 of photons are absorbed in the i-region, with a significant fraction of photons passing though the active region. (b) If however light can be scattered into a lateral mode, a much higher proportion of phonon can be absorbed in the active region, since the lateral extent of a fast p-i-n photodiode is many times the thickness of the i-region. For conceptual clarity changes in refractive index between the air and the layers are ignored in the diagram.