Preventing Metallic Contamination in Image Sensors

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Image sensors are among the fastest growing category of integrated circuits, due to the increasing proliferation of smartphones, industrial sensors, and security equipment. Because they involve both photodetection and signal processing, both CMOS image sensors and charged coupled devices (CCDs) are considerably more complex than many other integrated circuits. This results in several additional challenges in manufacturing image sensors with high production yields. This article discusses the specific need for minimal metallic contamination in image sensor devices and how to best achieve this.

The light sensitive portion of an image sensor is called the photodiode. In modern image sensors, the photodiode consists of a reversed-biased p-n diode. Electron-hole pairs are generated in the body of the diode by the incoming photons. The reverse biasing creates a wide depletion region in the p-n junction region of the photodiode. Electrons and holes generated in the depletion region are quickly separated and swept in opposite directions by the strong electric field in the depletion region. This allows the photon induced charge to be segregated and counted by the pixel electronics. In a (nonexistent) ideal photodiode, the relationship between the incoming photon count during the sample period and the collected charge would be perfectly linear. In real photodiodes, current is always measured by the pixel electronics that is not generated by the incoming photons. This current is referred to as the *dark current*, because it is determined by measuring the pixel output when there are zero incident photons on the photodiode. The dark current is a key metric of image sensor performance, it should be as low as possible. A high dark current results in poor image sensor low-light sensitivity and poor signal-to-noise ratio.

Most, but not all, of the dark current in an image sensor is due to either impurities or crystal defects in the silicon that forms the current path from the photodiode to the pixel readout electronics. Both impurities and crystal defects create “traps” in the silicon bandgap, i.e. discrete allowed energy levels in the forbidden bandgap between the valence and conduction bands. These traps significantly lower the energy required for undesired electron (or hole) tunneling between the valence and conduction bands (lengths of arrows in Figure 1). The left side of Fig. 1 indicates no trap present. In this case, the electron must tunnel the full bandgap energy to reach the conduction band. The center of figure 1 shows an impurity trap T_1 that is closer to the conduction band than to the valence band. The limiting factor for tunneling in this case is the larger of the two energy gaps, between the valence band and the trap T_1. (The tunneling would be similar if T_1 were located closer to the valence band by the same amount.) Trap T_2 on the right side of the figure is located midway between the conduction and valence band. This minimizes the highest energy gap that must be crossed for the electron to transition to the conduction band, leading to maximum tunneling. Since tunneling processes increase exponentially as the energy gap is reduced, trap T_2 will cause the highest tunneling, usually referred to as the *generation current*. This generation current cannot be distinguished from photon-induced current and will be misinterpreted by the pixel readout circuit as light impacting the photodiode.

Dark current issues can be divided into two cases. The first is the low-level dark current that affects many or most of the pixels in an image sensor. The result is poor low-light sensitivity, but the image sensor is still usable. The other case is where one or a handful of pixels has a dark current equivalent to the photon-induced current from a bright light on the pixels due to a high localized concentration of metals or defects (or both). Such pixels will appear bright white on all outputs of the image sensor, ruining the image quality and making the sensor unusable.

Successful image sensor fabrication therefore requires minimizing contamination of the silicon by elements that cause traps in the silicon bandgap, especially those with traps near the midpoint of the bandgap. Table 1 lists trap energies for metals commonly encountered in silicon processing. Equipment manufacturers must strive to keep silicon contamination with these elements to an absolute minimum.

The Axcelis Optima XEx high energy implanter excels at fabricating photodiodes with minimal energy contamination due to the unique filtering capabilities of its RF linear accelerator. A linear accelerator is essentially a velocity filter, only ions with the desired velocity will be accelerated down its entire length. Ions with the wrong velocity (i.e. those of a different mass, energy, or charge state than the desired ions) will quickly encounter a decelerating potential due to the time-varying RF acceleration field and be deflected away from the linac exit. The linac velocity filtering is so sensitive that the ^{10}B in natural boron can be completely filtered out from the ^{11}B implanted into the wafer, despite a mass difference of only 10% (Figure 2). Removal of the dangerous source transition metals in table 2 will be even more effective, because of the higher mass differences between these contaminants and the desired dopants. This makes the Optima XEx the best choice for advanced image sensor manufacturing.

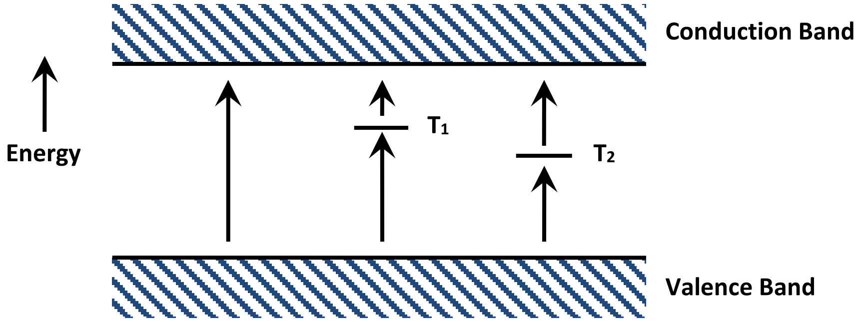

Figure 1: Illustration of trap-assisted leakage in silicon. The leakage current increases steadily in the examples from left to right.

Element	**Trap Energy (eV above the Valence Band)**	**Donor / Acceptor**
Ag	0.76	A
Ag	0.33	D
Au	0.58	A
Au	0.29	D
Co	0.59	A
Co	0.49	A
Co	0.35	A
Cr	0.71	D
Cu	0.53	A
Cu	0.40	A
Cu	0.24	A
Fe	0.98	D
Fe	0.61	D
Fe	0.40	D
K	0.86	D
K	0.35	D
Mg	1.01	A
Mg	0.87	A
Mo	0.79	D
Mo	0.34	D
Mo	0.30	D
Na	0.35	D
Ni	0.77	A
Ni	0.23	A
Pt	0.87	A
Pt	0.36	A
Pt	0.30	D
Sn	0.87	D
Sn	0.27	A
Ta	0.98	D
Ta	0.69	D
Ti	0.91	D
W	0.90	D
W	0.82	D
W	0.75	D
W	0.34	D
W	0.31	D
Zn	0.57	A
Zn	0.26	D

Table 1: Energies of mid-gap states (traps) introduced by common contaminants in silicon. Note that some elements introduce multiple traps at differing energies. The closer the trap energy to the midpoint of the bandgap (0.56 eV above the valence band) the more efficient the free carrier generation process. Donor levels assist electron tunneling, while acceptor levels assist hole tunneling.

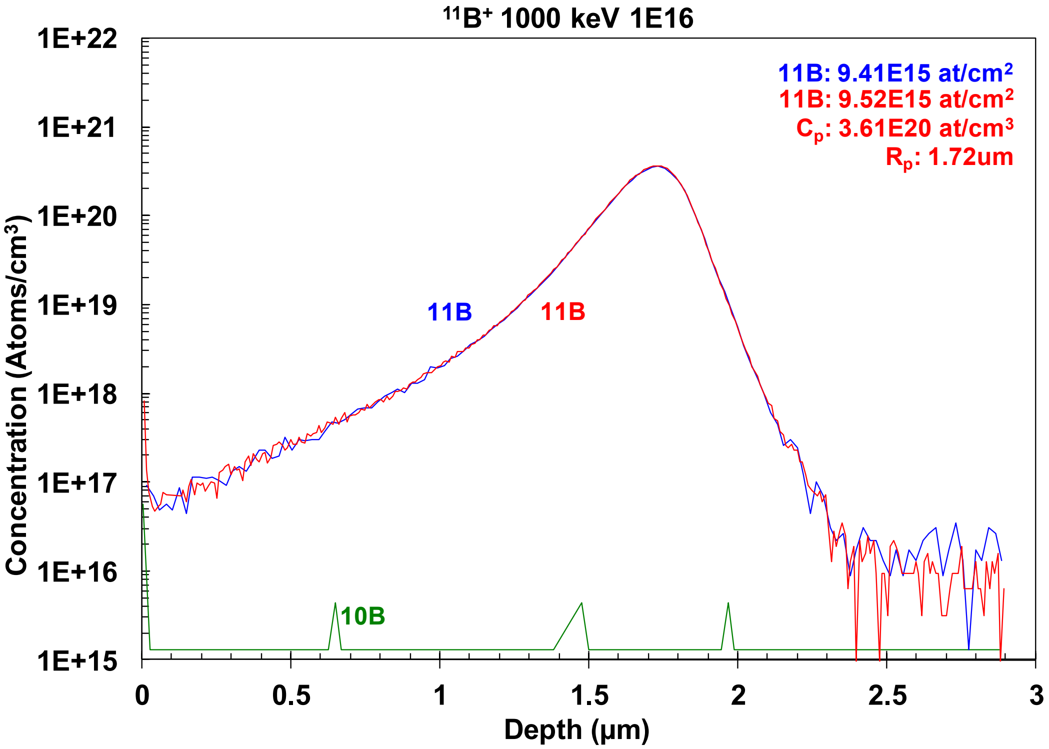

Figure 2: SIMS data from a very high dose boron implant on the Optima XEx. Despite the 20% natural abundance of ^{10}B in the source, it is undetectable in the wafer due to the velocity/mass filtering effect of the linac.