

AMORPHOUS SEMICONDUCTORS USHER IN DIGITAL X-RAY IMAGING

Unlike other major medical imaging methods, such as computed tomography, ultrasound, nuclear medicine and magnetic resonance imaging—all of which are digital—conventional x-ray imaging remains a largely analog technology. Making the transition from analog to digital could bring several advantages to x-ray imaging: Contrast and other aspects of image quality could be improved by means of image processing; radiological images could be compared more easily with those obtained from other imaging modalities; the electronic distribution of images within hospitals would make remote access and archiving possible; highly qualified personnel could service remote or poorly populated regions from a central facility by means of “teleradiology”; and radiologists could use computers more effectively to help with diagnosis—work that has already been initiated at the University of Chicago by Kunio Doi and his coworkers.¹

The conventional (analog) method for obtaining x-ray images is to use a cassette containing film held in position behind an intensifying phosphor screen. The screen absorbs x rays, gives off light and exposes the film, which is subsequently processed to form a final image.

Digital radiography is currently practiced through the use of three commercial approaches, two of which also depend on phosphor screens. The first of the phosphor-based approaches is to digitize the signal from a video camera that is optically coupled to an x-ray image intensifier to provide an instant readout.

The second phosphor-based approach is a stimutable phosphor system,² in which the phosphor contains traps for electrons excited by incident x rays. The latent image formed by the trapped electrons is then brought out, in the form of a blue-light image, by illuminating the phosphor, point to point, with a red laser. Unlike the intensifier system, the stimutable phosphor system cannot produce instant images, for the cassette must be carried to a laser scanner for readout by a photomultiplier, which performs the digitization.

The third commercial digital system is based on using an amorphous selenium photoconductive layer to convert x-ray photons directly to charge carriers. Called Thoravision, this is the digital chest x-ray imaging system recently introduced by Philips Medical Systems.³ It uses an amorphous selenium (a-Se) photoconductor sensitized by depositing

The same photoconducting materials that made photocopying possible in the 1960s are now poised to provide a basis for convenient, fully digital radiography.

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charges on its surface from a corona discharge, as in xerography. After exposure to x rays, the image resides as a charge distribution on the a-Se surface, which is read out electrostatically and then digitized.

None of the three systems has adequate image quality for all applications.

The major problem with the systems based on phosphor screens is poor resolution—a consequence of the spreading of light in the thick layer necessary to stop the energetic x rays. Thoravision's problem is not its image quality but the bulk and operation of the equipment. It cannot be housed in most existing radiographic rooms, and its huge rotating drum must be kept exactly 0.1 mm from the electrometers that measure the charge. There is still a strong need, therefore, for a convenient digital radiography system to read out images electronically, directly and with better image quality.

Flat-panel detectors

Recent developments in flat-panel display technologies have enabled flat-panel detector systems to capture the whole x-ray image and to provide a readout in digital form. In our opinion, the most promising and exciting new system is based on an x-ray photoconductor, such as a-Se, combined with an active matrix array to create a flat-panel x-ray image detector.^{4,5} This kind of detector captures the x-ray image and converts it directly to a digital signal for display, processing and storage. Higher resolution is possible because the charge carriers released by the absorption of x rays can be guided to the photoconductor surface by an electric field with negligible lateral spreading. (It is also possible to have a flat-panel system based on indirect conversion, using a phosphor layer to stimulate the emission of light and an array of photodetectors to convert the light to an electrical signal.⁶ This intermediate approach, though easier to realize at present, does not yield all the advantages of a digital system.)

An important first step in flat-panel x-ray detector technology was the development of displays made up of individual flat-panel thin film transistors (TFTs). These displays are also called active matrix arrays (AMAs), reflecting the fact that the active devices—the TFTs—are arrayed in a large matrix. The development of AMAs reached maturity when the fabrication of extensive films of hydrogenated amorphous silicon (a-Si:H) became technologically possible in the early 1990s. Flat-panel displays are also being developed using TFTs made from microcrystalline silicon and polycrystalline cadmium selenide.

Once large-area flat panels with small pixel sizes became readily available as electronic components, it was only a matter of time before an x-ray photoconductor would be used to directly convert x-ray images to a charge distribution stored on the pixels of a flat panel. The

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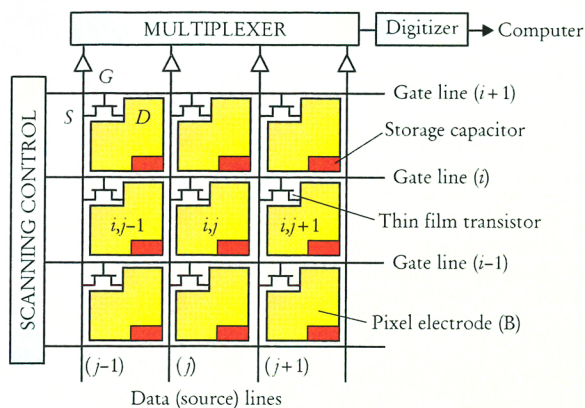
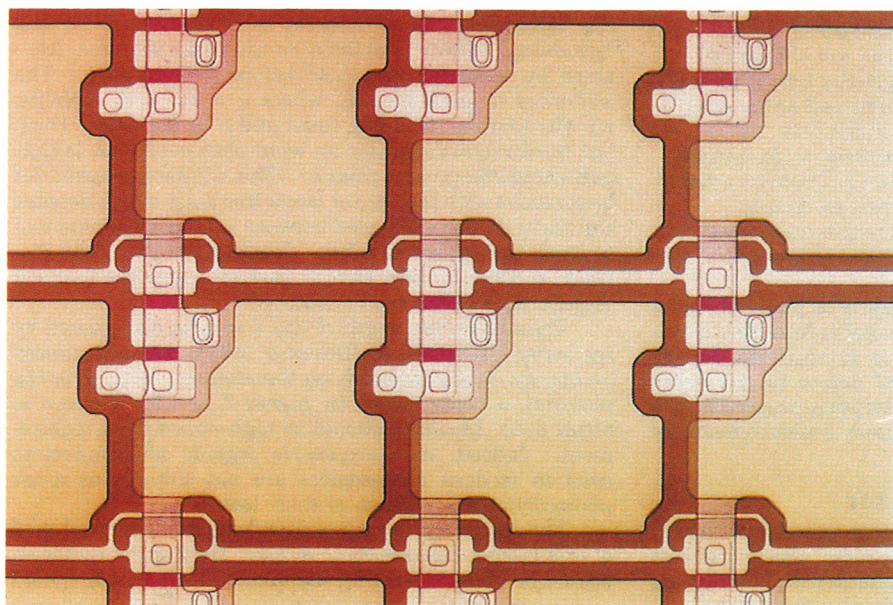


FIGURE 1. PART OF AN ACTIVE MATRIX ARRAY of thin film transistors. The photograph shows an area of 3×3 square pixels under an optical microscope, whereas the diagram illustrates how the same pixels are connected and read out. The labels “ i ” and “ j ” denote rows and columns, respectively. The charge stored on each pixel is determined by the amount of incident radiation and the conversion efficiency of the x-ray photoconductor. Rows are scanned sequentially from $i = 1$ to M ; the parallel data ($j = 1$ to N) on the pixels of an activated row are multiplexed and converted to digital information.



combination of an active matrix array and an x-ray photoconductor constitutes a direct conversion x-ray image detector (a term coined by E. I. du Pont de Nemours & Co). “Direct conversion” here refers to the fact that the x-ray photons are converted to charge directly,⁷ rather than indirectly by means of light photons from a phosphor screen, as in other flat-panel sensors.

One of the most interesting aspects of the development of flat-panel detectors has been the key role played by various amorphous solids: The substrate (glass), the thin film transistors (a-Si:H) and the photoconductor (a-Se) are all noncrystalline solids. Possessing only short-range order, amorphous solids lack the periodic arrangement of atoms that exists in crystals.⁸ This lack of structural rigidity means that such materials as a-Se alloys, unlike crystalline photoconductors, can be readily spread over large areas—a distinct advantage in medical radiology, since the lack of a convenient means to focus x rays necessarily results in a shadow image that is larger than the body part to be imaged.

Active matrix arrays

A typical AMA, as shown in figure 1, consists of millions of individual pixel electrodes connected by transistors (one for each pixel) to electrodes passing over the whole array to subsidiary electronics on the periphery. The TFTs act as switches to control the line-by-line clocking out of image

charge. Very large area (30×30 cm², for example) AMAs are now becoming available, and even larger ones will be possible in the future.

In general, an AMA consists of $M \times N$ (1280×1536 , for example) TFT-based pixels labeled i, j . Each pixel carries a charge collection electrode B connected to a signal storage capacitor C_{ij} , whose charge can be read by properly addressing the TFT _{ij} by way of the gate line i and source line j . Electronics and software outside the AMA convert the charges read on each C_{ij} to a digital image by self-scanning, as explained below.

To create a flat-panel sensor, a layer of a-Se is coated over the AMA to serve as an x-ray photoconductor, as shown in figure 2. Then, on top of the a-Se layer, an electrode is deposited so that a biasing potential can be applied to create an electric field across the a-Se layer. Electron-hole pairs (EHPs) generated in the photoconductor by the absorption of an x-ray photon travel along the field lines, the holes accumulating in the signal storage capacitor C_{ij} . The resulting charge signal Q_{ij} can then be read during self-scanning.

The interconnection of TFTs in an AMA is as follows: All TFTs in a row have their gates connected, whereas all TFTs in a column have their sources connected. When gate line i is activated, all TFTs in that row are turned on. The N source lines from $j = 1$ to N then read the charges on the pixel electrodes in row i . These parallel data are multiplexed into serial data, digitized and then fed into a computer for imaging. The scanning control then activates the next row, $i + 1$, and all the pixel charges in this row are read, multiplexed and so on, until the whole matrix has been read from the first to the last, M th row.

High resolution and high sensitivity make this system a leading contender in high-resolution, low-dosage digital radiography, as recently patented and discussed in the literature.^{4,5} The resolution is determined by the pixel size, which in present experimental image detectors is typically around $150 \mu\text{m}$ but can be made small enough ($50 \mu\text{m}$, for example) in future detectors to achieve the resolution necessary for mammography.

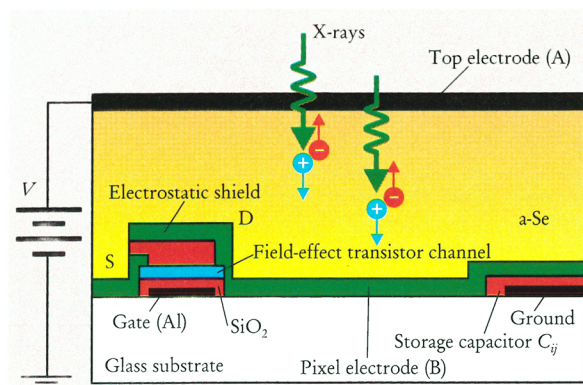


FIGURE 2. CROSS SECTION OF A SINGLE PIXEL (i, j) with a thin film transistor showing the accumulation of x-ray-generated charge on the pixel electrode and, hence, storage capacitor (exaggerated scale). The area of a typical pixel is $150 \times 150 \mu\text{m}^2$. The photoconductive layer is vacuum coated onto a flat-panel active matrix array and carries a top electrode for biasing and applying an electric field. Its thickness is typically 200–500 μm , depending on the imaging application. Under x-ray irradiation, each pixel carries a charge proportional to the incident radiation because the a-Se photoconductor in that region becomes more conductive.

Figure 3 shows an x-ray image of a phantom hand obtained by an experimental flat-panel a-Se sensor developed by John Rowlands's group at Sunnybrook Health Science Centre. (Here, "phantom" refers to a dummy object that replicates the x-ray absorption properties of a human body part. Using a phantom avoids repeatedly exposing a patient to x rays.)

An ideal x-ray photoconductor

One of the first x-ray photoconductors tested successfully for use in digital radiography was a-Se, which had also been the first choice as a photoreceptor in the photocopying process.⁹ (See Joseph Mort's article on xerography in *PHYSICS TODAY*, April 1994, page 32.) In both cases, the rationale was the same: a-Se can easily be applied as a thick film to coat large areas without altering its physical properties. And it is also highly sensitive to x rays, a key requirement. Even though a-Se may not be perfect, it is very promising, as demonstrated by the high quality of the images in figure 3.

Before we examine the photoconducting properties of a-Se, it is instructive to consider in general terms the five requirements that constitute an ideal x-ray photoconductor.

First, the ideal x-ray photoconductor should, of course, have excellent x-ray photoconductivity. This means that the amount of radiation energy $W_{\pm}$ required to create a single free EHP must be as low as possible because the charge ΔQ generated from an incident radiation of energy ΔE is simply $\Delta E/W_{\pm}$ —a relation well established by experiment. In semiconductors, $W_{\pm}$ is a material property, which increases with the bandgap energy E_g . High x-ray sensitivity implies a lower $W_{\pm}$ and, hence, a lower E_g .

Second, the ideal photoconductor should have negligible dark current. Since low dark conductivity is found in semiconductors with wider bandgaps, this requirement conflicts with the need for a low value $W_{\pm}$ to increase sensitivity. The dark current can be limited by depositing noninjecting electrical contacts—ideally, blocking contacts—on the photoconductor. With perfect blocking contacts, dark current is controlled by the rate at which charge carriers are thermally generated from various defects or recombination centers in the bandgap. On the other hand, the blocking contacts must allow charges generated by the x rays to exit the photoconductor to constitute the signal.

X-ray absorption generally occurs over a substantial portion of the detector thickness. Electrons and holes, therefore, should be able to travel farther, before being trapped, than the thickness L of the detector—otherwise, charge trapping would prevent the carriers from reaching the electrodes. This property is characterized by the "schubweg," which is defined as the mean distance traversed by a carrier in a field before it is trapped. The schubweg is given by $\mu\tau E$, where μ is the drift mobility, τ is the lifetime (trapping time) and E is the field. Thus, our third requirement for an ideal photoconductor is that $\mu\tau E$ should be greater than L . (The schubweg should not be confused with the carrier mean free path, which denotes the mean distance traveled between scattering events and controls the carrier mobility. Schubweg is the mean distance drifted by the charge carrier along the applied electric field before being captured.)

The absorption depth of the x rays is determined by the x-ray absorption coefficient α , which depends greatly on energy. It also depends on the atomic number Z of the material, α being larger for higher Z ($\alpha \propto Z^n$, where n is about 3–5). Ideally, Z should be high—our fourth requirement. Indeed, the inexpensive organic semiconductors used in modern photocopiers are not suitable as x-ray photoconductors because of their low Z .

The fifth requirement arises from the beneficial goal of minimizing the radiation dosage: Most of the radiation should be absorbed within the detector—that is, L should



FIGURE 3. AN X-RAY IMAGE OF A PHANTOM HAND obtained using a flat-panel a-Se-based detector.

be greater than $1/\alpha$.

These five requirements result in an important interplay—and an inevitable compromise—between α , L and the carrier *schubwegs*. For example, at an operating field of $5 \text{ V } \mu\text{m}^{-1}$, the *schubwegs* in device-quality a-Se are typically in the range of 3–6 mm for holes and 1–2 mm for electrons. The absorption depth ($1/\alpha$) of 20 keV photons is about 0.05 mm, but it is 1 mm for 60 keV photons. Clearly, operating at high energies requires a partial compromise between full absorption and *schubweg*-limited sensitivity.

A photoconductor's preparation requirements are just as important as its physical properties. If the flat-panel detector is to fit into today's x-ray imaging environment, the photoconductor must be prepared in large areas ($25 \times 25 \text{ cm}^2$, for example) without loss of uniformity. Also essential are reasonable substrate temperatures, practical deposition rates for achieving thick films and practical source temperatures—all of which have to be compatible with today's flat-panel technology. Furthermore, the photoconductor deposition step has to be economically competitive with other technologies. Amorphous materials, such as a-Se, a-Si:H and amorphous arsenic triselenide, are particularly suited for large-area applications because of their convenient preparation methods. As one of the oldest photoconductors, a-Se uniquely fits into this new large-area technology.

Amorphous selenium's practical advantages

A distinct advantage of a-Se is that it can be readily prepared as thick films or layers over large areas by straightforward thermal evaporation in a conventional vacuum coater. This basic vacuum deposition process was used extensively to fabricate photoreceptor drums based on a-Se for the photocopying industry from the early 1960s to the late 1980s. Vitreous selenium pellets (resembling beads) are loaded into a stainless steel boat, which is resistively heated by passing a large current through it. Selenium vapor condenses onto the AMA substrate to form a layer of a-Se.

Amorphous selenium melts at a relatively low temperature (about 220°C) compared with many other photoconductor materials, and its glass transition temperature is $40\text{--}50^\circ\text{C}$. Typical boat and substrate temperatures are $250\text{--}280^\circ\text{C}$ and $65\text{--}70^\circ\text{C}$, respectively—low enough to spare the flat-panel AMA and its delicate peripheral electronics from damage. Moreover, since typical deposition rates are $2\text{--}4 \text{ } \mu\text{m}$ per minute, a $200 \text{ } \mu\text{m}$ photoconductive coating can be applied in less than an hour.

In addition to being convenient to prepare, flat-panel sensors are cost effective because the AMAs used are available as off-the-shelf components.

There are, of course, many semiconductors that can also be vacuum-deposited, but they generally result in polycrystalline films and require annealing at high temperatures (hotter than 200°C for lead iodide) to eliminate structural defects. Furthermore, grain boundaries in polycrystalline films can trap charge carriers, limiting charge transport to the point of rendering the photoconductor useless. (In this case, the *schubweg* is much less than the photoconductor thickness.)

Density of states

Because of its xerographic importance in the 1970s, a-Se is one of the best-studied elemental amorphous semiconductors.¹⁰ But despite the wealth of data, there is still much challenging physics left in interpreting the properties of a-Se and how they are related to its structure. What remains to be done is more than simply fine tuning the physics and also has wider implications for other amorphous semiconductors.

History of Imaging with Amorphous Selenium

Sixty years ago, Chester Carlson, a patent officer at P. R. Mallory Co, invented xerography to do away with the drudgery of working with the old-fashioned photocopier, which actually used photographs.⁹ Operating such a photocopier involved loading a film cassette in a darkroom and, after exposing it, taking it back to the darkroom for developing—precisely the same multistage process that the use of films and screens imposes on present-day radiology departments. To solve the problem, Carlson sought a material that was sensitive to radiation (in his case, light rather than x rays), uniform in imaging properties to a very fine scale (an amorphous material is entirely free from granularity) and could be easily and cheaply spread over large areas. The material he and his collaborators at Battelle Memorial Institute eventually decided upon was amorphous selenium. Of course, for a photocopier, the system had to be compatible with toner—the charged ink powder that is used to print the copy. Today, the a-Se photoreceptors in photocopiers have been largely replaced with organic photoconductors, which are cheaper to produce. However, for x-ray imaging, a-Se is an ideal large-area photoconductor.

The density-of-states diagram is the key to understanding the properties of a-Se. (See figure 4.) As they drift through the photoconductor, electrons and holes interact with shallow and deep traps. Shallow traps reduce the drift mobility, whereas deep traps prevent the carriers from crossing the photoconductor. Since electrons and holes are indeed mobile in a-Se, their mobilities are believed to be controlled by shallow traps. Specifically, the effective electron drift mobility μ is equal to the conductivity mobility μ_0 in the extended states just above the conduction band, but reduced by the trapping and release of electrons in shallow traps about 0.35 eV below E_c , the energy of the conduction band. Similarly, hole drift mobility is controlled by shallow traps about 0.28 eV above E_v , the energy of the valence band.

Even though the exact nature of the shallow traps in a-Se has not been established, the drift mobilities of both holes and electrons are remarkably well defined and reproducible. By contrast, in many polycrystalline photoconductive layers, the drift mobilities are controlled by scattering from grain boundary defects, which depends on the morphology of the film and, hence, on the preparation conditions.

When charge transport is controlled by shallow traps, the carrier *schubweg* per unit field $\mu\tau$ depends on the concentration of deep rather than shallow traps. Consequently—and usefully—those impurities that introduce shallow traps do not affect the *schubweg*.

Amorphous chalcogenide (group VI) semiconductors are free from dangling bonds but suffer from the thermodynamic presence of what are called valence alternation pair (VAP) defects.⁸ This discovery was an important development in understanding the structure and properties of amorphous chalcogenide semiconductors. In the case of a-Se, VAP defects correspond to a positively charged, triply bonded center Se_3^+ and a singly bonded, negatively charged center Se_1^- , as illustrated in figure 5. It turns out that the deep localized states near the middle of the energy gap in figure 4—those responsible for deep electron and hole trapping—are believed to be the Se_3^+ and Se_1^- defects, respectively.

Experiments carried out at Xerox Research Laboratories during the 1980s showed that these deep states are thermodynamically derived—that is, they are equilibrium

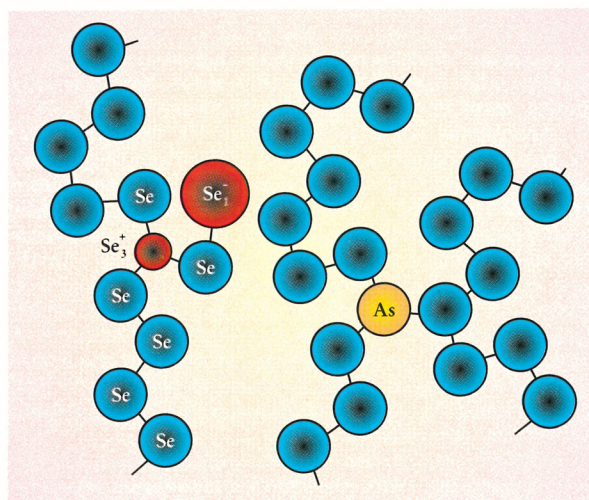
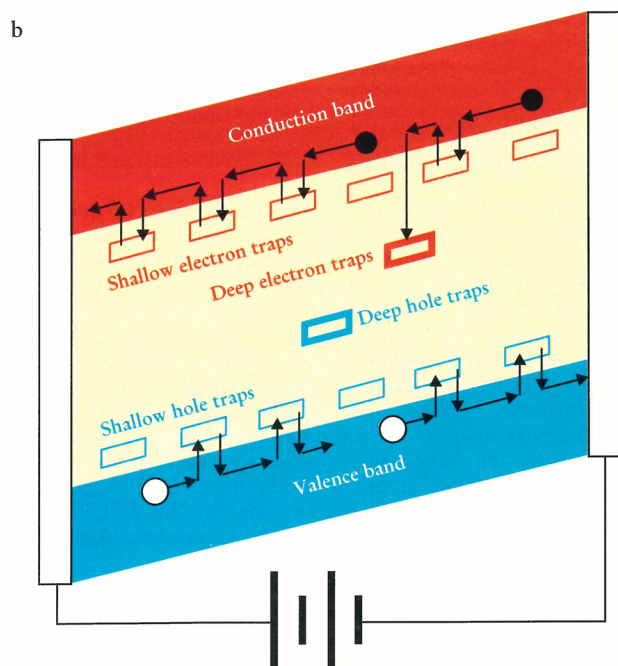
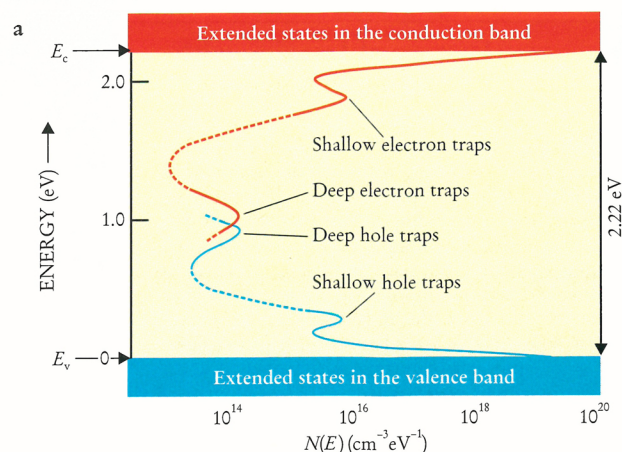


FIGURE 4. DENSITY-OF-STATES DIAGRAM of amorphous selenium (a). The states between E_v and E_c are localized states. The diagram was derived from data combined from transient photoconductivity, xerographic residual potential and other measurements (adapted from M. A. Abkowitz, *Philosophical Magazine Letters*, volume 58, page 53, 1988). X-ray photons generate electron-hole pairs throughout the bulk of the semiconductor (b). Drift of both electrons and holes involves interactions with shallow and deep traps. Shallow traps reduce the drift mobility and deep traps prevent the carriers from crossing the photoconductor.

defects, which cannot, therefore, be eliminated from a-Se. Since they control the carrier lifetimes, or trapping times, they determine the carrier schubwegs and, hence, the photoconductor performance. The introduction of impurities and alloying elements into a-Se provides additional sources of structural VAP defects, thereby shifting the balance between Se_3^+ and Se_2^- . This makes it possible to control the charge transport parameters of a-Se by chemical modification.¹⁰

The other—and main—reason for working with doped and alloyed a-Se is that pure a-Se crystallizes over time—months to years, depending on the ambient temperature and other conditions. Crystalline selenium has orders of magnitude greater dark conductivity than a-Se, which makes it unsuitable as an x-ray photoconductor. After much research at Xerox and RCA research laboratories, it was found that alloying pure a-Se with small amounts of arsenic (0.3–0.5% As) and doping it with 10–30 parts per million of a halogen (chlorine, for example) has two advantages. Most atoms of As (which has a valency of III) in the structure are triply bonded and link some of the Se chains (figure 5). The resulting increase in viscosity is sufficient to prevent crystallization. However, adding As introduces deep hole traps, which reduces the hole schubweg. To counteract this adverse effect—completely, in fact—chlorine is added in the 10–20 ppm range.

Although the compensation effects of As and Cl are still a subject of topical interest,¹¹ it is thought that adding As and Cl in these amounts provides the right balance of VAP charged defects and results in good hole and electron transport. Accordingly, the x-ray photoconductor used in flat-panel detectors is “stabilized a-Se”—that is, a-Se:0.3%As doped with 10–20 ppm Cl. Its optical and electrical properties are similar to those of pure a-Se.

Thanks to its wide bandgap of 2.22 eV and small concentration of localized gap states (as apparent in figure 4), a-Se has a relatively lower dark current than other amorphous semiconductors. Under blocking contacts, it is the thermal generation of charge carriers from these mid-gap states that usually controls the dark current in such semiconductors. The electrical contacts to many amorphous chalcogenide semiconductors are ohmic, and the current-voltage characteristics either represent bulk conduction (that is, the material conductivity) or conduction limited by space charge (the spatial distribution of injected charge carriers in the photoconductor).

Amorphous Se seems to be an exception in that there is an extensive disagreement in the literature about the reported behavior of its electrical contacts. And because

FIGURE 5. THE STRUCTURE OF AMORPHOUS SELENIUM has Se chains with undercoordinated and overcoordinated charged defects, Se_3^+ and Se_2^- , called valence alternation pairs (VAPs). These VAPs are believed to be responsible for deep hole traps and deep electron traps in a-Se. A small amount of arsenic (0.3–0.5%) is added to a-Se to link some of the chains, thereby increasing the viscosity and hindering crystallization.

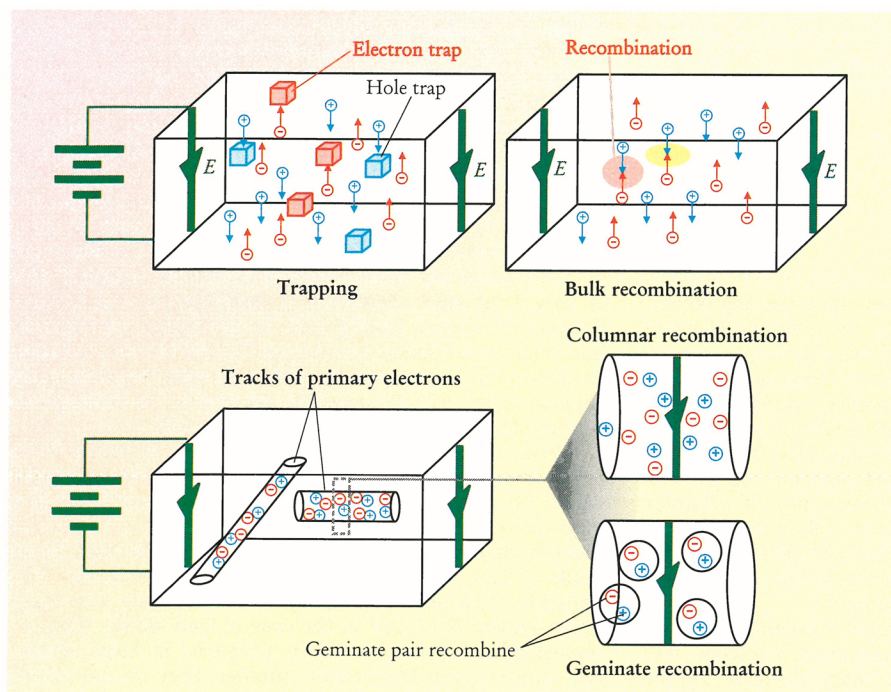


FIGURE 6. FOUR POSSIBLE MECHANISMS that reduce the number of collected (free) electron-hole pairs and hence reduce the x-ray sensitivity. Upper left: trapping of electrons and holes. Upper right: bulk recombination. Lower left: columnar recombination (bimolecular recombination within primary electron tracks) and geminate recombination (the recombination of an electron-hole pair created at the same time and bound by their mutual Coulombic attraction).

a-Se was first used as a xerographic photoreceptor, there was no urgent technological need to understand its contact effects, as the top surface was free for corona charging. Further, a-Se was deposited onto oxidized aluminum substrates (copier drums) and the substrate contact was “reasonably blocking”—that is, it did not allow electrons to enter the photoconductor to reach and discharge the surface potential. Understanding the physics of the metal contact effect in a-Se remains one of the main challenges in improving a-Se for flat-panel detectors.

Quantum efficiency

The study of optical quantum efficiency (QE) in a-Se during the late 1970s was one of the most fundamental in the field of low-mobility solids. It was shown that the QE depends on the field, photon energy and temperature. Specifically, Damodar Pai and Rudy Enck at Xerox were able to demonstrate that QE is controlled by the Onsager mechanism for the dissociation of an EHP generated by the same photon.

In many low-mobility solids, the initial EHPs generated by the absorbed photon remain mutually attracted by their Coulombic interaction because they are not able to diffuse far enough apart during the thermalization process. As the pairs diffuse in the amorphous structure, there is a certain probability that they will escape recombination. The applied field encourages the escape process, which gives the QE a characteristic S-shaped field dependence: It is constant at very low fields, then increases with the magnitude of the field until saturation. The same Onsager model for QE has been successfully applied to many other low-mobility solids.¹² It should be noted, however, that Daniel Moses’ recent experiments on subnanosecond transient photoconductivity¹³ have seriously challenged the Onsager mechanism as an explanation, reopening the debate on the physics of optical QE in low-mobility solids.

EHP creation energy and sensitivity

The study of a-Se’s QE was driven by the technological importance of a-Se’s photosensitivity to the photocopying

industry. Now, the technological importance of a-Se in x-ray imaging is driving the study of the EHP creation energy W_+ , a key parameter in the overall sensitivity and performance of the x-ray detector. Its physics, like that of QE, must be reasonably well understood to achieve the necessary gain for an optimized x-ray detector.

The creation of EHPs by an incident energetic particle or an x-ray photon first involves the ejection of an energetic primary electron from an inner core shell—the K shell, for example. As this energetic photoelectron travels in the solid, it successively ionizes atoms along its track, thereby creating many EHPs. For many semiconductors, W_+ has been shown to depend on the bandgap energy E_g and obey Klein’s rule¹⁴ through $W_+ \approx 2.8E_g + E_{\text{phonon}}$. The phonon energy term E_{phonon} is expected to be small (less than 0.5 eV), so that W_+ is typically close to $2.8E_g$.

So accurately is W_+ defined in crystalline semiconductors, such as highly pure germanium, that these materials are used in spectrometers to measure the energy of x rays or high-energy charged particles. Recently, William Que and Rowlands¹⁵ argued that since crystal momentum is not conserved in amorphous semiconductors, the value of W_+ should be about $2.2E_g + E_{\text{phonon}}$, where E_{phonon} is again small.

The case of a-Se has proven difficult to understand, for the measured values of W_+ —just like QE—depend strongly on the electric field. The lowest or saturated W_+ , denoted by W_+^0 , has been estimated only by extrapolation to high fields, but seems to be in the range of 4–6 eV. With $E_g \approx 2.2$ eV for a-Se, we would expect that $W_+^0 \approx 5$ eV.

The importance of clarifying W_+ in a-Se is twofold. First, its characterization in terms of a particular process is useful in modeling x-ray photoconductor behavior, which in turn helps in evaluating detector performance. For instance, the detector designer would be able to predict the conversion efficiency at different electric fields, operating x-ray energies and temperatures. At present, with no clear physical model, we can characterize the photoconductor only over a limited range. Second, as in the case of optical photogeneration efficiency, physicists are simply curious to learn what controls the conversion efficiency and what fundamentally determines W_+^0 .

There are various possible explanations for the field dependence of the EHP creation energy. The primary electron generates many EHPs, but only a certain fraction of them are collected, as illustrated in figure 6. Some disappear as a result of recombination, whereas others become trapped as they drift across the photoconductor. If we assume that practically no carriers are lost due to trapping—a requirement of device-quality photoconductor material—then the recombination losses can be plausibly explained by three mechanisms.

The first is simple bulk or bimolecular recombination between drifting electrons and holes. Because the recombination rate is proportional to both the hole and electron concentrations, the collected charge ΔQ would not increase linearly with the radiation intensity. However, since all experiments show that ΔQ does increase linearly with the x-ray intensity, this type of recombination is ruled out.

The second mechanism is geminate recombination, in which the simultaneously generated electron and its hole twin are attracted to each other by their mutual Coulombic force and may eventually recombine. This is the basic model for optical QE, and the number of EHPs collected—that is, that escape geminate recombination—is believed to be governed by the Onsager model.¹²

The third mechanism, columnar recombination, involves the recombination of nongeminate electrons and holes in the columnar track of a primary electron. As the intensity of the radiation is increased, the number of tracks increases proportionally. However, since these tracks very rarely overlap, the recombination within a track remains unaffected. Consequently, the collected charge increases linearly with the intensity—in agreement with observations.

The question then is whether Onsager or columnar recombination controls the field dependence. Further experiments are needed, particularly on the energy and temperature dependence of W_+ , to understand the origin of the x-ray sensitivity of a-Se and other low-mobility solids.

The future

We believe that the flat-panel detector coated with an x-ray photoconductor such as a-Se provides one of the best ways to realize the benefits of digital radiography. Thanks to its simplicity, compactness, and overall superior performance, the flat-panel detector will soon be used for various clinical x-ray tasks.

In particular, the flat-panel detector has potential for use in fluoroscopy—that is, real-time interactive x-ray imaging. In fluoroscopy, a video image on a monitor enables the radiologist to see a moving x-ray picture of the inside of the human body. This capability facilitates the diagnosis of function and guides such therapies as the use of balloon catheters to reopen blocked coronary arteries.

Since the benefits of digital radiography are so clear, its technological development is being pursued avidly—so much so, in fact, that some of the basic issues in x-ray photoconductor physics are still unresolved. This situation also occurred in the early development of xerography, the fundamental physics of which is still being studied today.

Recent research on operating a-Se photoconductors at high electric fields has revealed the feasibility of x-ray imaging devices unimagined a decade ago. There are two desirable reasons for operating at high fields. First, W_+ decreases with electric field, which leads to an improved x-ray-to-charge conversion. Second, a-Se at sufficiently high fields (in excess of $80 \text{ V } \mu\text{m}^{-1}$, for example) exhibits avalanche multiplication, which has been fruitfully and commercially used in supersensitive television pickup tubes by Kenkichi Tanioka and coworkers at the research department of the Japanese Broadcasting Corporation

(NHK).¹⁶ By making blocking contacts to a-Se, Tanioka has been able to build extremely sensitive photoconductive targets with avalanche gains as high as 600. These ultrasensitive targets, which are used in high-definition television sets, are known as HARP (high-gain avalanche rushing photoconductors). Gains as high as 600 imply an effective W_+ that is only a fraction of an electron volt and could translate into an improvement in image quality, especially in very low exposure techniques such as fluoroscopy. In fact, in the last few years, NHK has developed an x-ray-sensitive HARP tube, though with a target area of only $1 \times 1 \text{ cm}^2$. However, a supersensitive large-area flat-panel detector usable both in projection radiography and fluoroscopy seems feasible and could be realized soon. Even though the avalanche effect in a-Se has made the supersensitive HARP possible, its physics in amorphous semiconductors remains poorly understood.

Still to be resolved is whether a-Se can be perfected or whether replacing it with another x-ray photoconductor would be advantageous. Some initial research on new large-area x-ray photoconductors has been encouraging but not conclusive. For example, photoconductive layers made of lead iodide, thallium bromide and cadmium–zinc telluride show good sensitivity, but so far only over small areas—about $5 \times 5 \text{ cm}^2$ in the case of lead iodide. Organic photoconductors can be readily prepared in large areas,¹² but, due to their low atomic number, they do not absorb sufficient x rays and therefore cannot be used on their own. However, it may be possible to use a composite material based on dispersing x-ray absorbing particles in an organic binder, as recently reported by researchers at Du Pont.¹⁷ Whereas the benefits of direct conversion by using an x-ray photoconductor are known, the search continues for the perfect photoconductor.

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