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Photodetection and Measurement

MAXIMIZING PERFORMANCE IN OPTICAL SYSTEMS

MARK JOHNSON

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Maximizing Performance in Optical Systems

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Preface

The earliest I can recall an interest in optical detection was sometime around 1960. It was a project for an optically controlled model boat. All I can remember was that it used a handheld flashlight as transmitter and a light-dependent resistor on the model as receiver. Some rudimentary relay electronics taken from radio control provided the logic and memory to turn the boat on command, left, right, or straight ahead. I seem to remember it required some dexterity in flashing the light for about the right pulse-width to make it all work. I was desperate to make this, but with electronics knowledge limited to wiring batteries and bulbs, it was a hopeless endeavor.

Three years later, at school, we received some basic introduction to electronics, and it dawned on me that this would help with the old boat project. However, most of the time seemed to be spent with hole-cutters mounting valve sockets in aluminum chassis, winding component leads irretrievably around tag-strip connections, or in clearing the smoke from not-quite-correctly wired circuits. This wasn't what I had in mind for electronics, but it did at least engender some respect for high voltages, Ohm's law, and the ultimate thermal limitations of components. At about this time transistors became widely available, and I dropped thermionics almost for good.

When I started my research for a Ph.D. at London University, my colleagues and I needed to perform optical measurements, basic spectroscopy, loss measurements in planar optical waveguides, and optical fiber sensors demonstrations. It was usually possible to scrounge an old unmarked photodiode, and everyone seemed to point you to a high-performance electrometer from Keithley Instruments (analog of course). This was the pukka kit to use! However, no one seemed to have any idea how to use this beautiful voltmeter/ammeter. The technique seemed to be to connect the photodiode, spin the large rotary range selector until a signal was obtained, and see if it changed with your hand in front of the diode! I remember being incensed that no one knew the way to use it, or even whether the volts, amps or ohms scales would be best for my measurement.

That was thirty years ago, and since then I have had any number of similar experiences of "cluelessness." Generally I made the experiment work, and even had a few novel ideas along the way. At each impasse I tried to figure out what was needed to get it to work at all, and then to deliver the best performance possible. For almost every occasion, I realized years later how I *should* have done it to make it work much better.

In university labs there is usually a big community of "experts" who will tell you in broad terms how to solve some optoelectronic problem, or who explain in the mannerisms of an "old-soldier" how well they solved the identical problem years ago in some long-forgotten project whose details and project notes they can't recall, or who will "helpfully" say that you should be using a transimpedance amplifier or a Fourier transform or an avalanche photodiode, but when pinned down can't quite explain why, even less how actually to do it. So much voodoo is, for me, neither helpful nor encouraging. When all you want to do is solve the problem, it is much better if your guru can say "Do it this way, and it will work for these reasons." Almost as helpful is "I don't know, but let's go and find out."

Of course, it's not all voodoo. Several colleagues really have said "this is how you do it," and helped me greatly in the progress of many projects. One of my first was Bill McGarry at IBM's Thomas Watson Research Center, with his predilection for lots of gain, tamed with feedback, and back-of-the-envelope calculations of all the important issues. Robert Theobald of York Technology, with his feel for what kT/q really means, his vast store of issues convincingly thought through, and for a passion for making the "next one even better." Brian Elliott was also a fabulous inspiration, with his numerical rigor and dogged tenacity in understanding low-level electronic measurements and the physical processes underlying them, not just for electronics' sake but for the measurement or process under study. Then there were the companies, Ferranti, Mullard, Nexus, Philbrick, Analog-Devices, Burr-Brown, Zetex, and National Semiconductor, whose data-books and application notes I absorbed in a frenzy, and which sometimes changed the way I viewed the whole subject. And even the hobby stores, with their inspiring do-it-yourself projects, at once grossly overpriced on a cost-per-transistor level, and trivially cheap in didactic value.

Last, thanks to the Université Jean Monnet at St. Etienne in France, which gave me a month to lecture on the subject of optical detection, to try to find out what is important to the audience, and to think how to answer some of the difficult questions they posed. Without those questions, I don't suppose I would have ever gotten around to starting this book.

I know that this is not the most erudite work on the subject, and my level of understanding is a shadow of the authors whose books I read. Nevertheless, I seem to be able to see what might work, and to make it work in the limited sphere of laboratory optical measurements. Who is it for? The majority of physicists starting research work haven't done any electronics, at least not studied electronics in the sense of a real electronics course or spent ten years making his or her own HiFi and model aircraft. Professors will say that it doesn't matter, that the electronics department technicians will put together whatever you need. In practice they only do what you tell them, and, anyway, the little bits of electronics you need are so finely sprinkled throughout every working day that outsourcing is not efficient. You need to do it yourself. They even imply that electronics is somehow separate from physics, a kind of low-level support for your higher ideals. In my experience university research is littered with examples of good idea projects that were trashed because the first trials didn't work. They probably didn't work because the front end photodetector design was awful, the signal-to-noise ratio was a thousand times worse than it might have been, and it was connected to a computerized data acquisition system that didn't let you see how bad it was or how it could be fixed.

This book is for the physicist who has to get by in photo-measurement. It is designed to teach the new researcher working with modern optics the absolute basics of photodetection and the electronics that is so important to it, so that he can do good measurements, and spend more time thinking about the experiment. It is supposed to be practical, hands on, and tell you how you might really make it work. If it says an FET can make a good chopper, the next question has to be how? A useful text should say how.

Throughout the text are little experiments chosen to illustrate a point: TRY IT! They don't take much time (some are really basic) but they hopefully give a much better feel for what to expect in practice. Also in the text you will find occasional nonmainstream topics. These are aimed as an inspiration to look more widely at photodetection, modulation, coding, and even the mathematics of these processes, because the techniques that have been developed are often so elegant, and a few elegant ideas go a long way. If you look carefully at even the simplest of effects, there is always so much to see. Quick solutions to optoelectronic problems should leave you more time to look. When I apply the principles described here to optoelectronic measurements, they *almost always* eventually work. I hope that they work for you too.

Mark Johnson

ABOUT THE AUTHOR

Mark Johnson, Ph.D., is an independent consultant in opto-electronics and measurement innovation. He is a visiting professor at Salford University in England and St. Etienne University in France and has managed corporate research teams in the United Kingdom, the United States, and Germany. Dr. Johnson resides in Cheshire, England.

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Chapter 1

Photodetection Basics

1.1 Introduction

The junction photodiode that is the focus of this book has been described in detail in many other books and publications. Here only a few basics are given, so that you can use the photodiode effectively in real circuits. A simple model is presented that allows the main characteristics and limitations of real components to be understood. The ability to correctly derive the polarity of a photodiode's output, guess at what level of output current to expect, and have a feel for how detection speed depends on the attached load is necessary. The model we begin with has little to do with the typical real component fabricated using modern processing techniques; it is a schematic silicon pn-junction diode.

1.2 Junction Diodes/Photodiodes and Photodetection

Figure 1.1*a* shows two separate blocks of silicon. Silicon has a chemical valency of four, indicating simplistically that each silicon atom has four electron bonds, which usually link it to neighboring atoms. However, the lower block has been doped with a low concentration (typically 10^{13} to 10^{18} foreign atoms per cm^3) of a five-valent element, such as arsenic or phosphorus. Because these dopants have one more valency than is needed to satisfy neighboring silicon atoms, they have a free electron to donate to the lattice and are therefore called *donor* atoms. The donor atoms are bound in the silicon crystal lattice, but their extra electron can be easily ionized by thermal energy at room temperature to contribute to electrical conductivity. The extra electrons then in the conduction band are effectively free to travel throughout the bulk material. Because of the dominant presence of negatively charged conducting species, this doped material is called *n-type*.

By contrast, the upper block has been doped with an element such as boron,

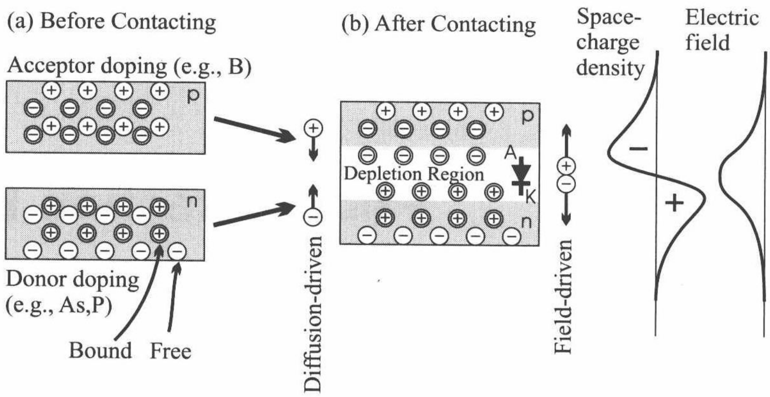

Figure 1.1 The pn-junction. The presence of predominately different polarities of free carriers in the two contacted materials leads to asymmetrical conductivity, a rectifying action. Bound charges are indicated by a double circle and free charges by a single circle.

which exhibits a valency of three. Because boron lacks sufficient electrons to satisfy the four surrounding silicon atoms and tries to accept one from the surrounding material it is termed an *acceptor* atom. As with donors, the bound boron atoms can easily be ionized, effectively transferring the missing electron to its conduction band, giving conduction by positive charge carriers or *holes*. The doped material is then termed *p-type*. The electrical conductivity of the two materials depends on the concentration of ionized dopant atoms and hence on the temperature. Because the separation of the donor energy level from the conduction band and the acceptor level from the valence band in silicon is very small (energy difference ≈ 0.02 to 0.05 eV) at room temperature the majority of the dopant atoms are ionized.

If the two doped silicon blocks are forced into intimate contact (Fig. 1.1*b*), the free carriers try to travel across the junction, driven by the concentration gradient. Hence free electrons from the lower n-type material migrate into the p-type material, and free holes migrate from the upper p-type into the n-type material. This charge flow constitutes the diffusion current, which tends to reduce the nonequilibrium charge density. In the immediate vicinity of the physical junction, the free charge carriers intermingle and recombine. This leads to a thin region that is relatively depleted of free carriers and renders it more highly resistive. This is called the *depletion region*. Although the free carriers have combined, the charged bound donor and acceptor atoms remain, giving rise to a space charge, negative in p-type and positive in n-type material and a real electric field then exists between the n- and p-type materials.

If a voltage source were applied positively to the p-type material, free holes would tend to be driven by the total electric field into the depletion region and on to the n-type side. A current would flow. The junction is then termed *forward-biased*. If, however, a negative voltage were applied to the p-type

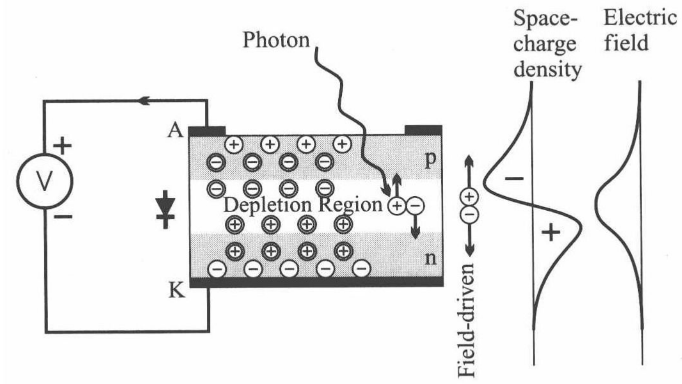

Figure 1.2 When a photon with energy greater than the material bandgap forms a hole-electron pair, a terminal voltage will be generated, positive at the p-type anode.

material, carriers would remain away from the depletion region and not contribute to conduction. The pn-junction is then called *reverse-biased*, and has very little current flow. Note that the diffusion currents driven by concentration gradients and the field currents driven by the electric field can have different directions. The conventional designation of the p-type contact is the anode (A); the n-type contact is the cathode (K).

This basic pn-junction diode model can also explain how a photodiode detector functions. Figure 1.2 shows the same diode depicted in Fig. 1.1 in schematic form, with its bound dopant atoms (double circled) and free charge carriers (single circled). A photon is incident on the junction; we assume that it has an energy greater than the material bandgap, which is sufficient to generate a hole-electron pair. If this happens in the depletion region, the two charges will be separated and accelerated by the electric field as shown. Electrons accelerate toward the positive space charge on the n-side, while holes move toward the p-type negative space charge. If the photodiode is not connected to an external circuit, the anode will become positively charged. If an external circuit is provided, current will flow from the anode to the cathode.

1.3 TRY IT! Junction Diode Sensitivity and Detection Polarity

The validity of this model can easily be tested. All diode rectifiers are to some extent photosensitive, including those not normally used for photodetection. If a glass encapsulated small signal diode such as the common 1N4148 is connected to a voltmeter as shown in Fig. 1.3 and illuminated strongly with light from a table lamp the anode will become positive with respect to the cathode. The efficiency of this photodiode is not high, as light access to the junction is almost occluded by the chip metallization. Nevertheless you should see a few tens of millivolts close to a bright desk lamp.

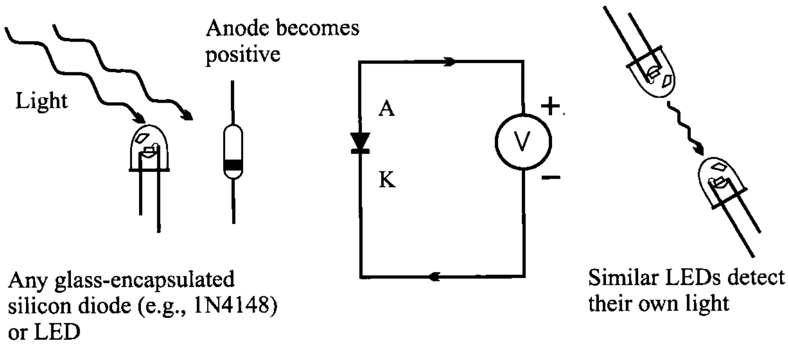

Figure 1.3 Any diode, even a silicon rectifier, can show photosensitivity if the light can get to the junction. LEDs generate higher open circuit voltages than the silicon diode when illuminated with light from a similar or shorter wavelength LED.

Rather more efficient are light emitting diodes (LEDs), having been designed to let light out of (and therefore into) the junction. Any common LED tested in this way will show a similar positive voltage on the anode. LEDs have the advantage of a higher open-circuit voltage over silicon diodes and photodiodes. This voltage gives an indication of the material's bandgap energy (E_g, see Table 1.1). Although with a silicon diode ($E_g \approx 1.1$ V) you might expect 0.5 V under an ordinary desk lamp, a red LED ($E_g \approx 2.1$ V) might manage more than 1 V, and a green LED ($E_g \approx 3.0$ V) almost 2 V. This is sufficient to directly drive the input stages of low voltage logic families such as 74 LVC, 74AC, and 74HC in simple detection circuits.

This works because the desk lamp emits a wide range of energies, sufficient to generate photoelectrons in all the diode materials mentioned. However, if the photon energy is insufficient, or the wavelength is too long, then a photocurrent will not be detected. My 470-nm blue LEDs generate negligible junction voltage under the desk lamp. Try illuminating different LEDs with light from a red source, such as a red-filtered desk lamp or a helium neon laser. You should detect a large photovoltage with the silicon diode, and perhaps the red LED, but not with the green LED. The bandgap in the green emitter is simply too large for red photons to excite photoelectrons. You can take this game even further if you have a good selection of LEDs. My 470-nm LED gets 1.4 V from a 660-nm red LED as detector but nothing reversing the illumination direction. Similarly the 470 nm generates 1.6 V from a 525-nm emitting green LED but nothing in return. These results were obtained by simply butting together the molded LED lenses, so the coupling efficiency is far from optimized. The above bandgap model suggests that LED detection is zero above the threshold wavelength and perfect below. In reality the response at shorter wavelengths is also limited by excessive material absorption. So they generally show a strongly peaked response only a few tens of nanometers wide, which can be very useful to reduce sensitivity to interfering optical sources. See Mims (2000) for a solar radiometer design using LEDs as selective photodetectors. Most LEDs are reasonable detectors of their own radiation, although the overlap of emission and detection spectra is not perfect. It can occasionally be useful to make bidirectional LED–LED optocouplers, even coupled with fat multimode fiber. Chapter 4 shows an application of an LED used simultaneously as emitter and detector of its *own* radiation.

For another detection demonstration, find a piece of silicon, connect it to the ground terminal of a laboratory oscilloscope and press a 10-MΩ probe against the top surface. Illuminate the contact point with a bright red LED modulated at 1 kHz. You should see a strong response on the scope display. This "cat's whisker" photodetector is about as simple a demonstration of photodetection as I can come up with! This isn't a semiconductor pn-junction diode, but a metal-semiconductor diode like a Schottky diode. It seems that almost any junction between dissimilar conducting materials will operate as a photodetector, including semiconductors, metals, electrolytes, and more fashionably organic semiconductors.

1.4 Real Fabrications

Although all pn-junction diodes are photosensitive, and a diode *can* be formed by pressing together two different semiconductor (or metal and semiconductor) materials in the manner of the first cat's whisker radio detectors or the previous TRY IT! demonstrations, for optimum and repeatable performance we usually turn to specially designed structures, those commercially produced. These are solid structures, formed, for example, by diffusing boron into an n-type silicon substrate as in Fig. 1.4 (similar to the Siemens BPW34). The diffusion is very shallow, typically only a few microns in total depth, and the pn-junction itself is thinner still. This structure is therefore modified with respect to the simple pn-junction, in that the diffusions are made in a high resistivity (intrinsic conduction only) material or additionally formed layer with a doping level as low as $10^{12}\,cm^{-3}$, instead of the $10^{15}\,cm^{-3}$ of a normal pn-junction. This is the *pin*-junction photodiode, where "i" represents the thick, high-resistivity intrinsic region. Most photodetectors are fabricated in this way. The design gives a two order of magnitude increase in the width of the space-charge region. As photodetection occurs only if charge pairs are generated close to the high-field depleted region of the structure, this helps to increase efficiency and

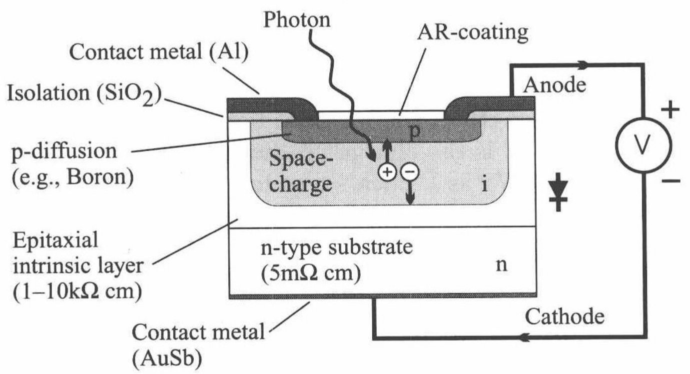

Figure 1.4 Most photodiodes are formed by diffusing dopants into epitaxially formed layers. The use of a low conductivity intrinsic layer leads to thickening of the space-charge region, lower capacitance, and improved sensitivity.