MSM photodiodes

A new, faster way to ensure lightwaves get their messages across

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Devices that detect light are fundamental to many consumer electronics as well as to the "information superhighway." For instance, a remote control for a VCR emits a wide beam of modulated infrared light via a light emitting diode (LED). The properties of semiconductors are thus exploited to convert electrical signals to optical signals. The emitted modulated signal, transmitted through the air, will include commands for the VCR to play, rewind, and so forth. However, the complimentary device, a photodetector, is needed to detect the modulated light at the VCR box and therefore recognize the issued commands.

The ultimate application, however, requiring high performing photodetectors is in fiber optic communications. Here, photodetector performance is being pushed to its limits. Currently, Japan and the United States are moving towards optical fiber communication systems that will transmit information at 10 Gb/s.

Japan's goal is more aggressive. It includes a plan to bring a nearly 10 GHz bandwidth signal via optical fibers to every home. This is referred to as fiber-to-the-home (FTTH).

U.S. companies are pursuing a more conservative course. They, instead, favor a hybrid approach that brings fiber-to-the-node (FTTN) or fiber-to-the-curb (FTTC).

In this scenario, a high bandwidth optical fiber reaches a local node for FTTN (which serves about 50-100 homes) or neighborhood switching station for FTTC (which serves 8-10 homes). Coaxial cables are then used for the remaining distance to the individual residences. However, coaxial cables have limited bandwidths of about 500 Mhz; whereas optical fibers can transmit terahertz signals and are only limited by the semiconductor receivers and transmitters at either end.

Even if FTTH is unrealistic for the near future, the 10 Gb/s optical fiber communications systems are still needed for the backbone links for voice and data transmission, say between Boston and Washington, DC. But at these speeds, very stringent demands will be placed upon the photodetectors used. These photodetectors must operate with bandwidths of almost 10 Ghz to obtain the necessary margin. That means that the photodetector must respond to every binary 1 and 0 on the order of tens of picoseconds (that's 10^{-12} seconds!).

At these speeds, highly functional optoelectronics integrated circuits (OEIC) will be required, such as photoreceivers with high speed photodetectors monolithically integrated with low-noise preamplifiers, to fully realize the bandwidth potential of the photodetector. Metal-semiconductor-metal photodiodes may have an advantage in this arena over conventional photodetectors.

Nuts and bolts of photodetectors

Let us first define the terms by which photodetectors are specified. A photodetector's performance is measured by its dark current, quantum efficiency, bandwidth (or speed) and spectral range. There are basically two types of semiconductor photodetectors: photoconductors and photodiodes.

Photoconductors are the simplest of semiconductor photodetectors and consist of a semiconductor material with two low resistance ohmic contacts. Light hitting the semiconductor which is larger in energy (hv) than the semiconductor band gap (E_g) is absorbed which creates electron-hole (e-h) pairs. The e-h pairs induce a change in the semiconductor resistivity which is measured by an external

circuit, either by amplifying the change in conductivity or collecting the induced photocurrent. Photoconductors are slow, but do exhibit gain.

Photodiodes can be made from p-n junctions in semiconductor materials, and are operated in reverse bias in its current vs. voltage (I-V) third quadrant. Without light incident, a small generation-recombination current, commonly called the dark current, flows which is the background noise. When light with energy $hv \geq E_g$ is incident, e-h pairs are generated. The electrons and holes are quickly swept to the positive and negative electrodes, respectively. Photodiodes can be very fast, but do not generally exhibit gain.

The quantum efficiency is a measure of how many e-h pairs are created per incident photon and then collected by the contacts to the external circuit. Quantum efficiency (η) is measured in terms of a percentage (less than 1 without gain). Internal quantum efficiency (η_{int}) compares the efficiency of the generated e-h pairs being collected by the contacts, whereas external quantum efficiency (η_{ext}) compares the incident photons to the collected photocurrent, thus convolving effects of surface reflections and the absorption constant (α) of the semiconductor. Internal quantum efficiency generally exceeds 90%, but without a proper anti-reflection (AR) coating of the photodiode surface, about 30% of the incident light is reflected off the semiconductor surface due to the differences in index of refraction of the semiconductor and air. This immediately limits η_{ext} below 70%.

The bandwidth, also known as the "3-dB frequency," of a photodetector is a measure of how fast the photodiode can respond to a series of light pulses. The 3-dB bandwidth is found by measuring the output power of a
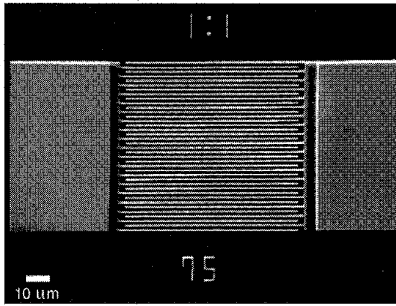
Fig. 1 A scanning electron microscope (SEM) photomicrograph of a fabricated MSM photodiode. The active area is 75x75 mm² with 1.0 μm wide electrodes and 1.0 μm gap spacings.

device as it adjusts to the varying frequency of the incoming light signal.

When plotted, a flat region should occur at low frequencies indicating a stable response. However, as the frequency rises, the photodiode response degrades. (It cannot respond to the signal as quickly as the light beam is modulated.) As a result, the response photocurrent falls. When the response falls 3 dB below the flat region, 50% of the power is lost. The frequency at this point is referred to as the 3dB frequency or the bandwidth of the device.

There are two time constants which limit the speed of a photodiode. One is the transit time. This is simply the time a carrier, created by a photon, takes to travel through the active region and get collected by the contacts at the device's edge. Photons are absorbed by the semiconductor by raising the potential energy of an electron in the valence band to the conduction band. The missing electron in the valence band is referred to as a "hole."

An electron and hole can have different mobilities, and the disparity can be ten-fold or more for direct band gap semiconductors, like GaAs, which collect and emit photons more efficiently than indirect semiconductors, like Si and Ge. Thus, holes take longer to traverse the photodiode active region than electrons, and therefore can limit the photodiode speed.

For instance, an active region might be 1 micron thick, and the carrier velocity (v_{sat}) is about 1 x 10^7 cm/sec. For this example, the transit time (t_{tr}) would only be 10 picoseconds, using:

$$t_{tr} = d/v_{sat} \tag{1}$$

where d is the distance the carriers travel, the upper limit will be the thickness of the active layer. The 3-dB frequency can then be calculated using:

$$f_{3dB} = \frac{\Gamma_d}{2\pi t_{tr}}, \tag{2}$$

where Γ_d varies from 2.4 for absorption of photons only at the surface to 3.4 for uniform absorption. A value of Γ_d equal to 2.8 is more realistic, which results in a bandwidth of 45 Ghz for our example.

The RC time constant is the other limiting factor. The product of the photodiode junction capacitance (C_j) and the equivalent resistance in parallel with C_j (usually 50 Ω governed by the measuring instrument and cabling) yields the RC time constant, measured in seconds.

Since photodiodes are typically one doped layer on top of another, they form a parallel plate capacitor. This junction capacitance is often quite large because of the typical area sizes used for photodiodes.

For example, take our 1 μm thick photodiode and make the area 100 μm in diameter. The capacitance can be calculated by

$$C = \frac{\varepsilon_s \varepsilon_0 \cdot A}{d} \tag{3}$$

where ε_s is the permitivity of the semiconductor (about 12) between the doped layers; ε_0 is the permitivity of free space (8.854x10^{-14} F/cm), A is the photodiode area, and d is the photodiode absorption layer thickness. This equates to 0.83 pF, which when multiplied by 50 Ω, results in about 40 picoseconds, or 3.8 GHz. Thus, the RC time constant, not the transit time, is limiting the photodiode's response for our example. Of course, the photodiode could be made very small to reduce Cj and thus the RC time constant, but then it becomes difficult to collect much light.

Those wavelengths the semiconductor is sensitive to are called the spectral range of the photodetector. For long wavelengths, the response cuts off abruptly when the light has lower energy than the semiconductor's band gap ($hv < E_g$). This is because the striking photon does not have enough energy to move an electron from the valence band to the conduction band.

At shorter wavelengths, the absorption constant of the light within the semiconductor rises dramatically. As the absorption rises, more light is absorbed closer to the upper surface of the semiconductor instead of uniformly throughout the active region. Since loss mechanisms, such as recombination currents are more prevalent at the surface, the photodiode response trails off also at shorter wavelengths. For long haul fiber optic cables, the attenuation minimum occurs at a wavelength of 1.55 μm. Indium gallium arsenide (InGaAs) is a suitable low band gap (~0.8 eV) material for the absorption of light at these near-IR wavelengths.
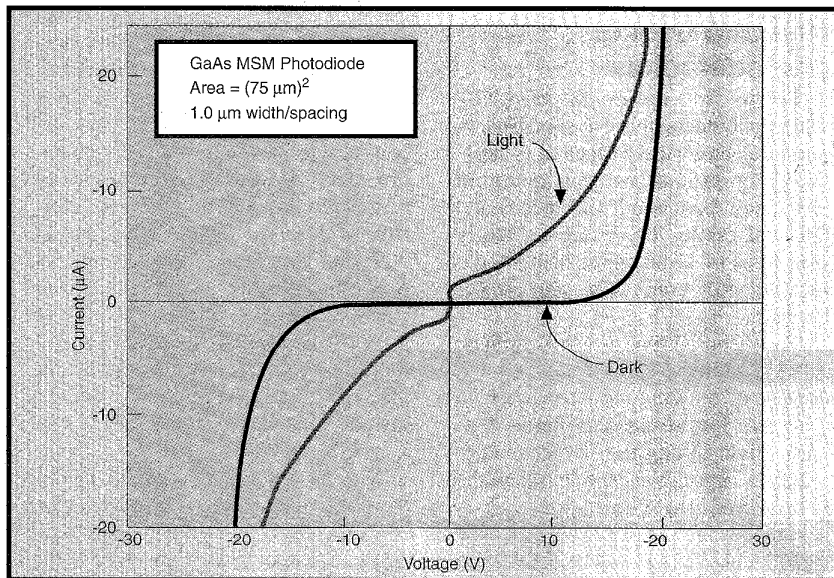

Fig. 2 I-V characteristics of a generic MSM photodiode under darkness and illumination.

Current photodiodes and their drawbacks

The most common semiconductor photodiodes are p-i-n photodiodes. These photodiodes make use of a p-n junction in a semiconductor material. Photodiodes do not generally have an internal gain mechanism. However, a modified photodiode, called the avalanche photodiode (APD), can exhibit gain when operated with large reverse biases. In this situation, ionization collisions can occur leading to multiplication.

To improve photodiode quantum efficiency (neglecting any gain mechanism), the photodiode absorption region is made much thicker to collect as much incident light as possible. This is accomplished by creating a sandwich of undoped, or intrinsic (i-region) material in the middle of two heavily doped contact layers. This results in a p-i-n photodiode. The i-region also contains fewer defects, caused by doping centers, which contribute to noise in the output electrical signal, thus suppressing the dark current. As the i-region is made thicker, quantum efficiency may rise, but the transit time will increase, thus lowering the bandwidth.

The "large area" p-i-n photodiode suffers in speed performance. This is because a p-i-n photodiode is basically a parallel plate capacitor: a highly doped p-type region on top of a highly doped p-type region with a dielectric material inserted between them. As a result, the capacitance tends to blur one digital waveform with the next. But, since capacitance is directly related to the size of the area (see Equation 3), the p-i-n photodiodes can be made very small (perhaps 5-20 μm in diameter).

The problem is that single mode fibers are preferred for long distance optical transmission to minimize dispersion. Also, single mode fibers have very narrow optical cores. The optical core of a single-mode fiber used in long haul fiber optic communications is only 8-10 μm in diameter. (A multi-mode fiber for local area networks (LAN), for instance, is much larger at around 50 μm in diameter.) This makes alignment of a small p-i-n photodiode with the fiber very challenging.

How MSM photodiodes work

Metal-semiconductor-metal photodiodes (MSM) are another, new class of photodetectors that offer an attractive
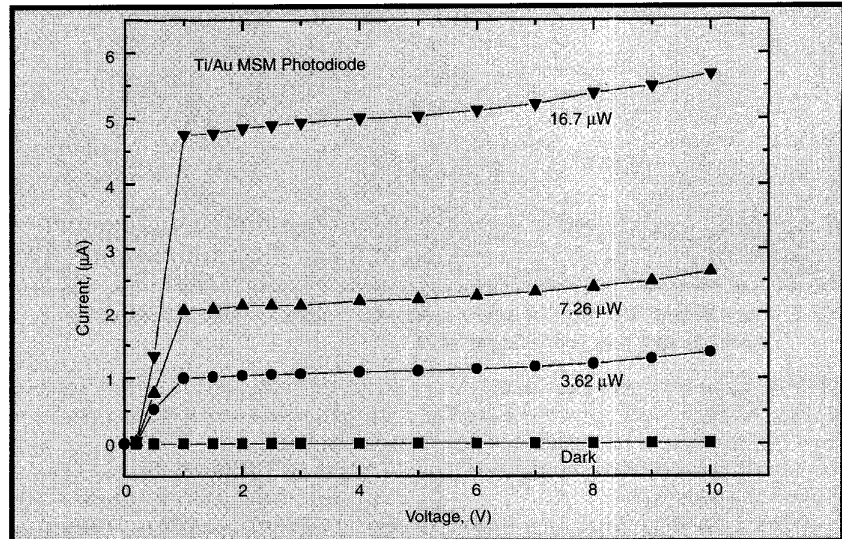

Fig. 3 *Response of the I-V characteristics of an InGasAs MSM photodiode to various levels of incident illumination.*

alternative. An MSM photodetector is comprised of back-to-back Schottky diodes that use an interdigitated electrode configuration on top of an active light absorption layer. A Schottky diode exhibits a rectified I-V characteristic like p-n junctions, but occurs at certain metal-semiconductor junctions. Unlike the potential barrier of a p-n junction which is controlled solely by the semiconductor doping levels, a Schottky diode's potential barrier (ϕ_B) is also ruled by the metal and semiconductor work functions. The key differences between a p-n and Schottky diode is that p-n junctions allow both electrons and holes to flow under forward bias, while a Schottky diode is a majority carrier only device. An MSM photodetector is inherently planar and requires only a single photolithography step for fabrication. A scanning electron microscope (SEM) picture of a completed MSM photodiode is shown in Fig. 1.

A basic MSM photodiode uses a layer of semiconductor material that is sensitive to the wavelength of interest. On top of this layer, the metal electrodes are deposited. Each set of electrodes forms a Schottky barrier contact with the semiconductor,

and is connected to a large pad for connection to the external circuit.

Since the two electrodes are connected serially, back-to-back, they form two diodes. A typical MSM photodiode I-V curve is shown in Fig. 2. Note, that one diode is always in reverse bias.

Figure 3 shows another MSM photodiode with a family of curves under various illumination intensities. The dark current is controlled by the reverse saturation current which is created by two mechanisms. One is the spontaneous creation of e-h pairs within the semiconductor's active region due to thermal energy. The second is due to carriers which overcome the Schottky barrier height. An energy band diagram of an
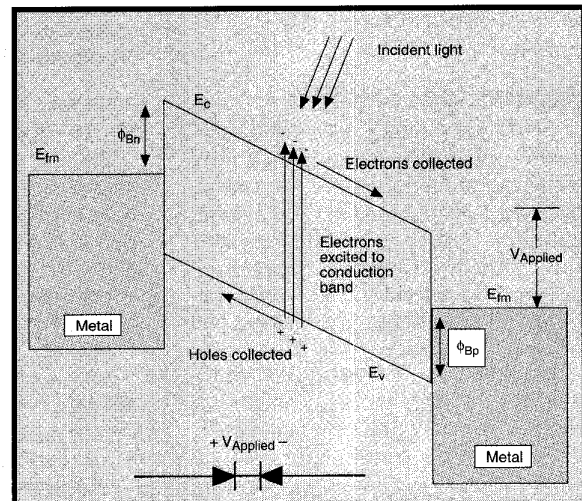

Fig. 4 *The energy band diagram of an MSM photodiode depicting the Schottky barriers (ϕ_{Bn} ϕ_{Bp}) of both metal-semiconductor junctions.*
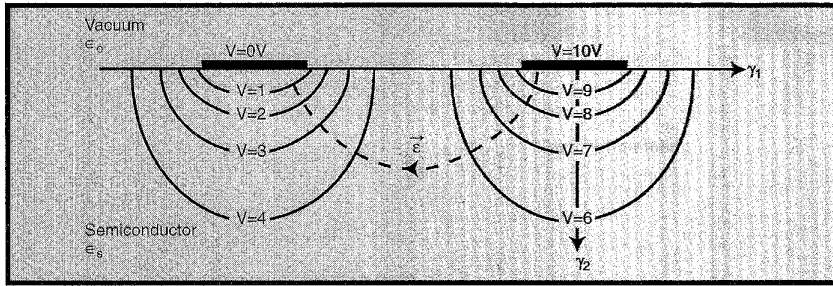
Fig. 5 The electric field lines of equal potential below the electrodes of an MSM photodiode (from Soole et al).

MSM photodiode under bias is shown in Fig. 4. This represents the Fermi level (E_f) position of the metals and the valence (E_v) and conduction (E_c) bands of the semiconductor.

When light impinges on the MSM photodiode, the light that hits the semiconductor surface is absorbed creating e-h pairs within the active region. If a 5-10 volt bias is placed across the two electrodes, then one set of electrodes acts as a cathode and the other as an anode. The e-h pairs divide with holes drifting towards the negative electrodes (under the influence of the electric field), and electrons traveling to the positive electrodes. (See Fig. 4.)

Figure 5 shows the electric field lines under these electrodes. When the photoinduced carriers travel towards the electrodes, a displacement current registers in the external circuit. When the final electron or hole reaches the electrodes, the photocurrent pulse in the external circuit ends. This photocurrent shifts the dark current I-V curve (see Fig. 3).

Advantages of MSMs

MSM photodiodes have the fundamental advantages of: 1) planarity; 2) simplicity of fabrication; 3) low capacitance per unit area, and 4) process compatibility with field effect transistors (FET). The low capacitance lends itself to large area detectors. This makes coupling to single mode fibers easier and without sacrificing bandwidth.

Ironically, a disparate portion of the total cost of optoelectronic components stems from packaging issues, especially those requiring critical optical alignments. Packaging issues traditionally have been overlooked since this type of work is considered less glamorous than working on the fundamental high-speed devices. However, if the package is designed improperly, the performance of a high speed semiconductor device is never realized.

Since MSM photodiodes can be made with large collection areas without significant speed degradation, they enable the critical optical alignments to optical fibers to be greatly relaxed. This ultimately reduces the high cost of optoelectronics, except for special purposes. If the cost of the optoelectronic compo-
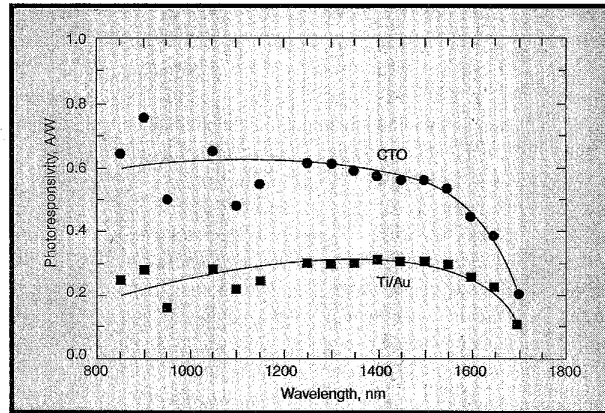

Fig. 6 Responsivity of two MSM photodiodes comparing transparent conductor (CTO) and opaque metal (Ti/Au) electrodes (from Gao et al).

nents was lowered, then FTTH might become a reality in the ensuing decade.

Another trend among optoelectronic components is using greater integration of discrete components into a monolithic form. To detect an optical signal, the light must be collected, converted from an optical signal to an electrical signal, amplified and, lastly, its integrity cleaned up.

Amplification and signal processing take place using transistors. The coupling of a photodetector with pre-amplifier circuitry as discrete components suffers from large connection wires. These wires, at high speeds, add an appreciable parasitic inductance. This can distort the signal and lower the speed response of the entire system.

However, the monolithic integration of MSM photodiodes with field effect transistors (FET) is very simple. This is because the electrodes of the MSM photodiode and the gate fingers of a FET can be defined with the same photolithographic step and then deposited with the same metalization. For example, Vitesse Semiconductor is currently selling 1 GHz photoreceiver modules using GaAs MSM photodiodes as the photodetector integrated with FET circuitry.

Disadvantages of MSMs

The drawbacks of MSM photodiodes are: 1) that very fine feature sizes are needed which could be difficult to fabricate; 2) that the MSM photodiode responsivity is poor, and 3) that the metal-semiconductor interface is hard to control reliably.

MSM photodiodes typically employ electrode configurations of 1 μm or less, which can be challenging. For instance, MSM photodiode electrode dimensions are much smaller than feature sizes associated with p-i-n photodiodes. They often reach sub-micron dimensions. However, these feature sizes are comparable to sizes of a typical gate length on a FET. For example, Intel's new P6 Pentium chip (130 MHz) uses 21 million transistors, all with 0.35 μm gate lengths.

MSM photodiode responsivities are lower than p-i-n photodiodes. The main causes for the low responsivity are:

1) reflections from the surface metals;

2) absorption of incident light outside the region in which photogenerated carriers can be collected by the electrodes; and

3) the finite carrier lifetimes caused by surface recombination currents and deep traps within the semiconductor material which cause the photo-generated carriers to recombine before ever reaching the electrodes.

However, transparent conductors such as indium tin oxide (ITO) and cadmium tin oxide (CTO) are being explored for use as the electrodes instead of opaque metals. These electrodes are transparent to the wavelengths detected, yet still conduct the

collected photocurrent. Thus, reflections off the electrodes can be eliminated, as shown in Fig. 6. However, their reliability is questionable.

Absorption of carriers in low field regions is easy to solve. If carriers are created deep in the active region (see Fig. 5), they first slowly diffuse to the junction edge. When the carriers reach the electric field lines created by the applied voltage, the carriers then drift at the saturation velocity towards the electrodes.

To eliminate this effect, the absorption region should be kept thin. The region should be only thick enough to absorb 60% to 85% of the incident light. Trying to collect the last 10-20% of the light with a thicker absorbing region greatly reduces the speed response, and leads to diminishing returns. Also, carriers created laterally outside the electric field lines can be prevented by creating a mesa etch. This removes unwanted semiconductor material from outside the active region. Thus, a pilar is created on top the semiconductor substrate. This common technique achieves electrical isolation as well, from one device to the next, if a semi-insulating substrate is used.

The finite carrier lifetime can actually be exploited. Since MSM photodiodes are basically transit time limited, the MSM speed can be enhanced by killing the free carriers, especially the slow hole current.

If high speed performance is desired at the sacrifice of high responsivity, the active region of an MSM photodiode can be made with many defect recombination centers on purpose. Many of the optically generated photocarriers will then never reach the electrodes before they are lost to recombination, which results in poor responsivity. Only carriers generated very near an electrode will be collected.

MSM speed is usually limited by a slow response tail while the heavier carriers (holes) as well as both carrier types from deep in the active region slowly travel to the electrodes. By quenching this tail and reducing the electrode spacing, the speed response can get as high as 510 GHz. Also, if the electrode spacing is made with sub-micron dimensions using electron-beam lithography, then many carriers can be collected before being lost to recombination.

Perhaps the most daunting problem associated with MSM photodiodes is that metal-semiconductor interfaces are very difficult to control. This issue pertains to the Schottky barrier height of metal-semiconductor junctions. The atoms on a clean semiconductor surface have unsatisfied dangling bonds. These bonds will try to minimize their free energy and react with oxygen or other elements. This can result in a significant amount of charge at the surface which can act to pin the semiconductor Fermi level.

As a result, the actual Schottky barrier height may not be controlled strictly by the difference in the metal and semiconductor work functions, as theoretically predicted. Some work has been done on passivating the semiconductor surface with various chemicals or plasma techniques to satisfy the dangling bonds of the semiconductor surface. Also, in-situ processing is being explored for mass wafer production. This process grows the active region in a vacuum environment and transfers the wafer directly to a metalization chamber without breaking the vacuum. Thus, surface contamination never occurs.

For narrow band gap materials, like InGaAs suitable for long-haul fiber optics, the Schottky barrier heights are very small. A small Schottky barrier destroys any rectification of an M-S junction. Any small signal is lost in the excessive dark current. However, very thin (200-800Å) layers of wide band gap semiconductors, like InAlAs (E_g~1.5 eV), could be inserted between the metal and low band gap absorption region. This technique works quite well.

However, problems with metal-semiconductor interfaces should not impede progress on MSM photodiodes. For example, metal semiconductor field effect transistors (MESFET) deal with these same issues. Alcatel and other companies now commonly use MESFET technology for the receiver and transmitter circuits in microwave communications satellites. The gate electrode for these MESFETs is simply a Schottky contact on a semiconductor surface. Also, as mentioned earlier MSM photodiodes are starting to find their way to the marketplace.

Conclusion

MSM photodiodes are becoming a viable option for light detection. MSM photodiodes are simple and, therefore, cheap to integrate with electronics. They also allow very large area detectors to facilitate coupling to optical fibers without degrading the bandwidth. Some manufacturing issues still exist which need to be overcome, such as reliability of metal-semiconductor Schottky contacts; but, MSM photodiodes are starting to appear in the marketplace. This trend is expected to continue.

Read more about it
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