Indium Gallium Arsenide NIR Photodiode Array Spectroscopy

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Spectrometers measure the light energy absorbed or reflected by a material. Prism spectrometers are the oldest (~ 2000 years) instruments whereby color measurements were made using the eye as the photoreceiver. William Herschel used a prism spectrometer in the 18th century to examine light beyond the red with the first photon detector: a blackened thermometer, now known as a bolometer. Since Herschel and Newton's time, spectroscopy has evolved as a separate field of science. An essential factor to this growth has been the advancements in photoreceivers. This paper concentrates on the near-infrared (near-IR) region of the spectrum between 800 and 2200 nm (approximately where silica-based optics become opaque). Indium gallium arsenide (InGaAs) is the best material for a solid-state detector, offering the highest sensitivity in the near-IR. It has become the detector of choice for near-IR spectroscopy.

Scanning monochrometers (prisms and diffraction gratings) with single-element photodetectors have been the mainstay in spectroscopy. Using silver-emulsion film technology, a complete spectrum (visible–short wave–near-IR) was obtained without the need of a moving dispersive element (hence, the name spectrograph was coined). This allowed the spectrometer to be moved into remote locations and initiated what became known as multichannel spectral analysis. With photodetector technology advances, linear and matrix photodiode arrays are becoming the detector of choice for remote monitoring. Real-time measurements of key on-line parameters are performed in process control, using diode-array spectroscopy. Uses of remote diode-array spectroscopy are found in agricultural, food, pharmaceutical, and petrochemical firms. Figure 1 illustrates a reflection grating spectrometer with a photodiode array.

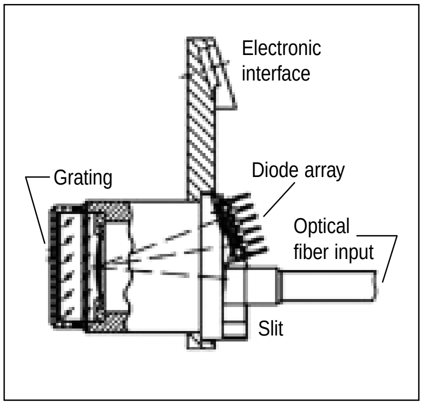

Figure 1. Diagram of a reflection-grating spectrometer with a photodiode array.

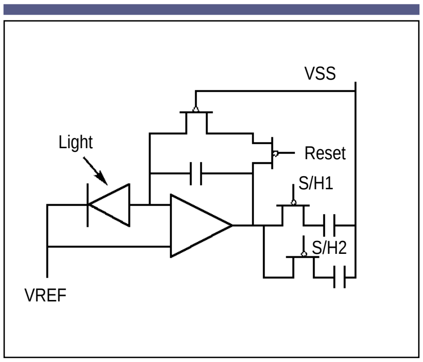

Figure 2. Schematic of an integrating transimpedance amplifier.

Linear detector arrays are available with thousands of individual photodiode elements (*pixels*) in a convenient, small package. Arrays having less than 64 elements can be operated in the parallel out configuration, in which each pixel is individually addressable with a separate amplifier. Longer arrays having hundreds to thousands of pixels are primarily operated in a serial-out arrangement, in which each pixel is amplified off-chip and sequentially read-out. The photodiode operates in the integrating mode rather than direct detection, wherein a capacitive transimpedance amplifier is the first-stage amplification circuit. Figure 2 illustrates the detection format.

These self-scanned linear arrays include on-board signal analysis electronics that perform operations such as *correlated double sampling*, a method to improve noise performance. Figure 3 illustrates an InGaAs photodiode array hybridized to a silicon readout integrated circuit. Hybridization is the principal array fabrication technique for nonsilicon materials such as indium antimonide, mercury cadmium telluride, indium arsenide, and InGaAs.

The array operation is straightforward: a predetermined exposure time is specified via a clock pulse, and the incident photons produce electron-hole pairs in the InGaAs absorption layer. These photocarriers generate a photocurrent that is processed by the off-chip capacitive transimpedance amplifier into a measurable voltage. After exposure, the array circuit serially outputs each element. A detailed description is beyond the scope of this note. Judicious selection of the source light and spectrometer (specifically, diffraction grating and optics) is necessary to optimize the detection process. The photodiode array's mechanical, optical, and electrical parameters are interdependent and affect system performance. The remainder of this article will highlight the performance parameters and operating techniques for a grating-based InGaAs photodiode array.

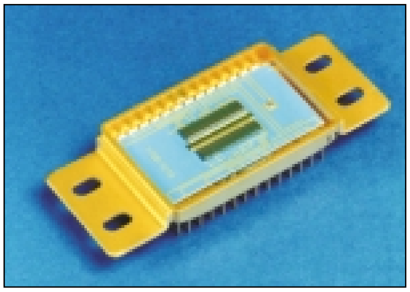

Figure 3. An InGaAs photodiode array hybridized to a silicon readout integrated circuit.

The principal mechanical parameters are array length, center-to-center spacing, element geometry, fill factor, and operability (number of nonworking pixels). Photodiode-array lengths are paired to the length (and availability) of the silicon readout integrated circuit (or multiplexer). Presently, commercial InGaAs photodiode arrays are available that range in size from 128 elements to 512
elements. The pitch or center-to-center spacing has been standardized to 50 µm; hence, array lengths are between 6.4 mm and 25.6 mm. The pixel geometry is rectangular with available heights ranging from 50 µm to 1 mm. Tradeoffs between size (area) and signal-to-noise ratio will determine the element selection.

InGaAs photodiode arrays have a 100% fill factor (ratio of active photoresponse area to element area). Thus, maximized light collection efficiency is realized compared with arrays having less than unity fill factor. Zero dropout arrays are common with 128 and 256 elements. System performance depends on the coordination of the components to match the array of the spectrometer, based on the application. Figure 4 is a photograph of the InGaAs photodiode array illustrating a 0.5-mm pixel on a 50-µm pitch.

The linear array is characterized by its opto-electronic performance parameters: dynamic range, dark signal, maximum output voltage (transimpedance gain), spectral responsivity, and maximum exposure and minimum (fastest) readout time. *Dynamic range* can be defined as the maximum usable output voltage divided by the root-mean-square (rms) multiplexer readout noise. There may be a perceived problem with this definition of usable output voltage. A distinction must be made between linear response and saturated response. As the photoelement approaches saturation, it can produce a nonlinear response (*supraresponsivity*). The preferred mode of operation of the array is radiometric, common to most spectrometers.

The lowest signal level is defined by the silicon multiplexer's readout noise. Neither the photon shot noise nor dark signal shot noise is considered here. The latter exclusion may seem unusual. Normally, the dark signal limits the performance; cooling the array enhances the dynamic range. Sometimes this helps, but there is no point in cooling an array such that the dark noise is much below the silicon multiplexer's read noise. The noise is uncorrelated, hence, the root-sum-square defines the total noise (see the following example). Performing at levels much below the read noise (temperature independent) does not help. Meanwhile, much money can be spent on a cooling system. Dynamic range is also used to determine the level of digitization and whether the operation is optimized for high sensitivity or high dynamic range. Selection will be based on the spectrometer and application.

The pixel dark signal is defined in units of volts per second to rapidly determine allowable exposure times as well as the more familiar definition of dark current in amperes. It is due to the nonzero input offset voltage of the multiplexer's capacitive transimpedance amplifier. This will either forward or reverse bias the photodiode producing a dark current. Additionally, this bias level can be different for each element, which produces dark signal nonuniformity — a component in fixed pattern noise (defined later in this article). In most cases, the dark signal is the dominant noise generator, especially during long exposures. An InGaAs photodiode element can have a dark current of 1 pA, corresponding to 6.25 Me/s. Photodiodes follow Poisson statistics and the rms noise value is the square root of the measured output. Thus, a 1-s exposure will produce a 6.25 Me dark signal having an rms noise level of 2500 e. Cooling the photodiode array will decrease the dark current and the noise. InGaAs photodiode dark signal is temperature dependent with the dark current doubling or halving with each decade of temperature. Operation at -10 °C reduces the dark current by a factor of eight (relative to 20 °C) and the dark noise is reduced by a factor of 2.83 (or 883-e noise level). However, if the readout noise is 2000 e, the root-sum-square noise is 2186 e, a 9% noise reduction. The extra effort required to cool the array for a 9% improvement might not be cost effective. Techniques are available to reduce the effects of dark signal such as offset correction, dark field subtraction, and multiple scans at shorter integration times.

The charge capacity in a capacitive transimpedance amplifier is determined from the integrating capacitance output voltage product. Diode arrays are available with multiple capacitors selectable to the specific application (for example, high sensitivity and high dynamic range). Consider the following example: the amplifier output is 2 V with an integrating capacitor equal to 10.4 pF, hence, the maximum charge capacity is 20.8 pC, corresponding to 130 Me. Because we are measuring voltages, the transimpedance gain is calculated to be 2 V/130 Me, which equals 15.4 nV/e or 11 nV/photon. Thus, the array's signal-to-noise ratio is simply the maximum charge capacity (sometimes called "full well") and shot noise level quotient.

The photodetector spectral response defines the maximum spectrometer free-spectral range. A single photodiode array covering the 800–2200 nm spectrum (allowable transmission band for silica-based lenses and optical fiber) is not available. Two InGaAs compositions have been commercially developed that cover the 800–1700 nm and 1100–2200 nm ranges. Selection of a particular wavelength range is dependent on the application and tradeoffs associated with the instrument performance.

Exposure time and readout time for diode arrays are temporally separated. The photodiode array, including the multiplexer, is first exposed (integration time), then deactivated and serially read-out. Commercially available photodiode arrays can have µsecond exposure and readout times. Exposure times are electrically generated (no mechanical shutter) via the control electronics. Readout times are specified by the number of samples read per second. Thus, a 512-element array operating at 2.0×10^7 samples/s has a 26 µsecond readout rate. The scan time is the sum of exposure and readout time; scan times of 50 µseconds (frame rates of 20 kHz) are

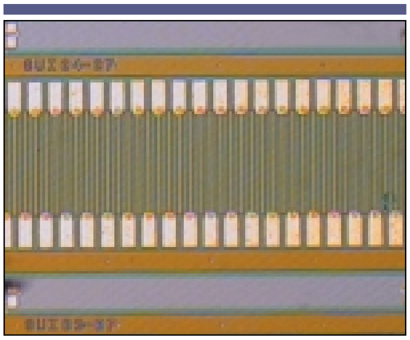

Figure 4. A linear InGaAs photodiode array.

possible. Because exposure times affect signal level, dark signal, photon shot noise, dark noise, and offset level, the specific exposure time in a spectroscopy application will depend on the experiment.

Diode-array spectroscopy uses optimization techniques to enhance the performance and reduce the degradation caused by nonuniformities that generate fixed pattern noise, reduce amplifier-based noise through correlated double sampling, and use the reciprocity law to detect weak signals. Correlated double sampling was mentioned earlier as a mechanism to reduce the noise caused by the capacitive transimpedance amplifier. The charge amplifier produces reset noise caused by its operation (resetting the capacitor for the next integration). This noise must be eliminated for accurate measurements. The design of the multiplexer is such that sample/hold circuits are used to hold the signal immediately after reset and then to subtract it from the signal obtained at the end of the exposure time. Reset noise is superimposed on both the dark signal (sample/hold 1) and the accumulated light plus dark signal (sample/hold 2). Subtraction yields only the light signal.

Fixed-pattern noise is caused by nonuniformities in the response of the photodiode array and multiplexer electronics capacitive transimpedance amplifier that distort the electrical output. This noise is nonrandom and remains stable from one scan to the next scan. Two factors contribute to fixed-pattern noise — dark signal nonuniformity and photo response nonuniformity. Gain and offset correction through flat-fielding and dark-fielding are the mechanisms for reducing the effects.

The principle of reciprocity simply states that the total signal charge is the product of the photocurrent and the total exposure time. It does not matter if the total exposure time is achieved using a single long exposure or by adding multiple shorter exposures. Reciprocity refers to the accumulation of signal charge. Care must be taken when analyzing the effect on the various components of the noise charge. This is another technique to improve signal-to-noise ratio when the dark current is large.

In conclusion, diode-array spectroscopy is becoming the instrument of choice for sensing in the process control industry. Its advantages — robustness on the factory floor, nonmoving parts, and rapid collection of spectra — provide the incentive to further look at this technology in areas that were previously the domain of the scanning spectrometer. A real-life application will be presented in the second installment of this discussion.

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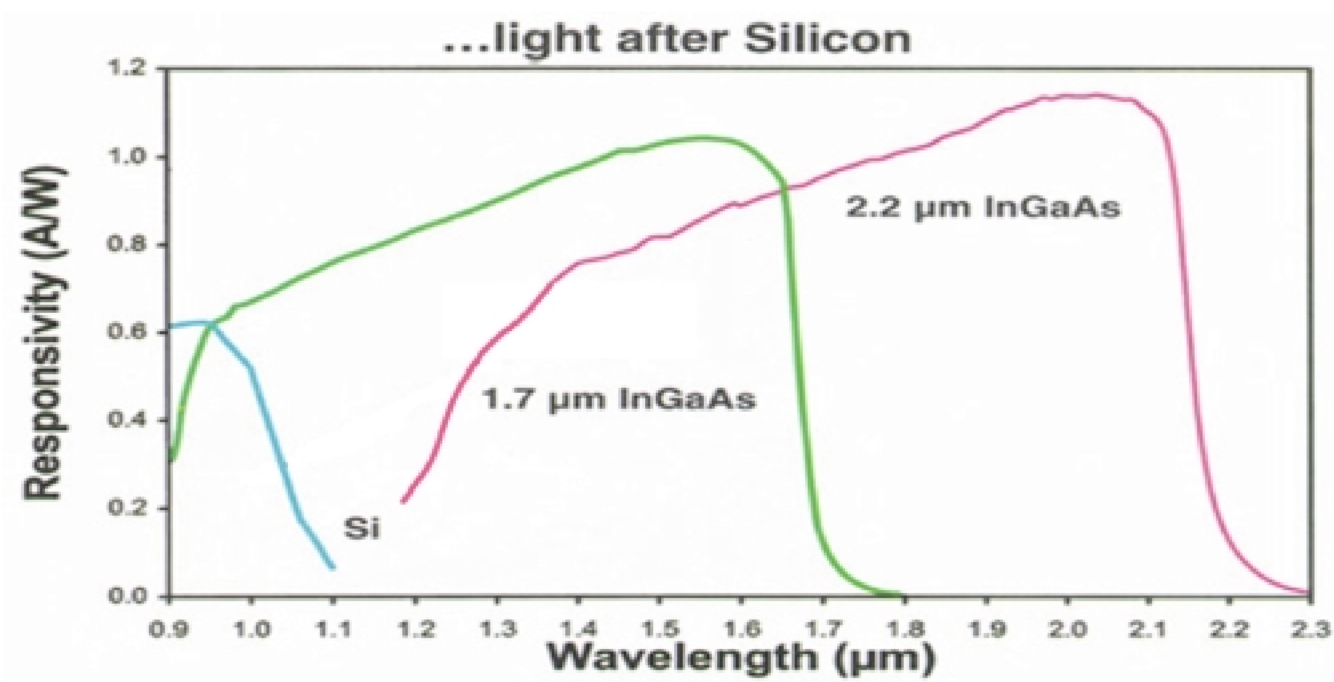

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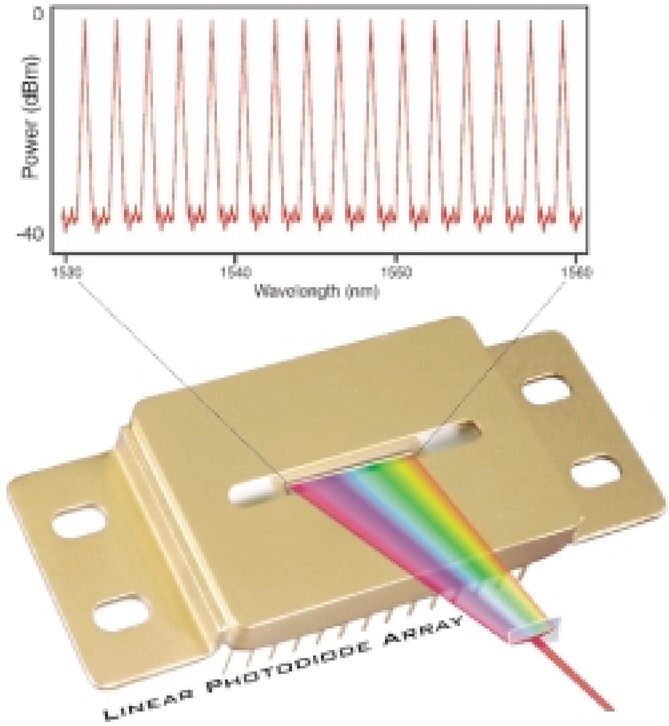
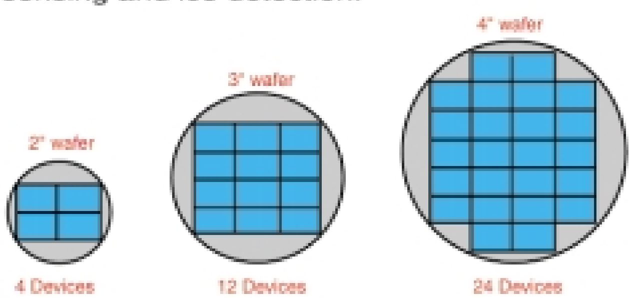


Our InGaAs linear photodetector arrays are used primarily in telecommunications and data applications such as dense wavelength division multiplexing (DWDM) fiber optic systems and in industrial spectroscopy. Sensors Unlimited was also the first manufacturer of InGaAs cameras and is recognized as THE world leader in this field, as well as for InGaAs detector products in general. Our room-temperature InGaAs cameras are used for laser beam diagnostics, inspection of fiber optics components, semiconductor wafer inspection, infrared sensing and ice detection.



Our success in FY 1999 was based large on sales to the telecommunications industry, fueled by the insatiable demand for bandwidth on the Internet, whose capacity nearly doubles every three months. Our "LX" detector arrays have become the industry standard for DWDM monitoring and our next generation "LY" array with 25 µm pitch will set the new standard for years to come. Sensors Unlimited's fundamental strengths with semiconductor materials, devices, R&D and marketing place us in an enviable position for the exploding growth of these industries.

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