Multispectral imaging sensors integrated on silicon

Jacopo Frigerio, Sergio Bietti, Giovanni Isella, and Stefano Sanguinetti

Quantum dot infrared detectors can be integrated on silicon using droplet epitaxy, enabling the simultaneous detection of multiple wavelengths in a format compatible with current semiconductor technology.

In imaging applications, simultaneous detection of multiple wavelengths enables enhanced information combined with lower false-alarm rates. Systems that collect data in separate spectral bands are capable of accurately determining the absolute temperature as well as obtaining unique signatures of objects in a scene. By providing this new dimension of contrast, multiband detection also enables advanced spectral processing algorithms to further improve sensitivity beyond that found in single spectral devices.

A multispectral imaging (MSI) device usually combines the detection of a wide range of wavelengths into a single optical system. The number and position of spectral bands in each sensor provides a unique combination of spectral information that can be tailored for specific applications in fields such as defense, environmental monitoring, gas sensing, and transportation. Current MSI systems rely on cumbersome imaging techniques that either disperse the optical signal across multiple IR imaging sensors or use a filter wheel to spectrally discriminate images focused on a single imaging sensor. These systems include beamsplitters, lenses, and bandpass filters placed in the optical path to focus images onto separate sensors responding to different bands.

These issues could be overcome with the implementation of a multispectral integrated sensor in which each element of the photodetection array is able to read multiple wavelengths in parallel, thereby providing MSI systems with improved reliability, speed, and portability. Moreover, integrated multispectral photodetectors are compatible by design with applications that require close alignment of spatial information from two or more spectral bands, such as image fusion. The trend toward multispectral capabilities integrated on a single device is clear in the recent evolution of imaging IR systems (see Figure 1).

No imaging sensor at present can detect from visible (VIS) to long-wave infrared (LWIR) ranges in parallel at the single pixel level. In fact, current sensors rely on a range of materials, each of them optimized for a precise spectral range. Narrow-gap semiconductor detectors, such as mercury cadmium telluride, currently represent the dominant technology, especially in the LWIR regime. Other important IR detector technologies are based on indium antimonide for mid-wave infrared (MWIR) applications.
and arsenic (As) doped silicon (Si) impurity band conductors for very-long-wave infrared (VLWIR) applications. It is extremely challenging to obtain multispectral capabilities within each single element of a photodetection array. In this context, the integration of an IR imaging sensor within microelectronics based on complementary metal oxide semiconductors (CMOS) could open the door to high-resolution MSI in which visible and IR radiation are detected simultaneously.

VIS light is detectable by a standard CMOS imaging sensor, while a specialized multiband IR detector can provide the MWIR-LWIR imaging capabilities. In this respect, quantum dot infrared photodetectors (QDIP), which exploit optically stimulated transition between conduction bands within quantum dots (QDs), can be used for IR sensing. As they are based on quantum confinement effects, the absorption wavelength can be tuned to the desired value by engineering the shape and dimension of the QD. While all photosensitive devices are subject to a small electric current in the absence of incident light (dark current), QDIPs are expected to show a low dark current due to the three-dimensional confinement of charge carriers. Confinement hinders electron-phonon interaction, allowing for superior signal-to-noise ratios and reducing the power required for detector cooling.\(^2\) Moreover, QDIPs have high tolerance to crystal defects.

We developed a QDIP based on strain-free gallium arsenide (GaAs) QDs embedded in an aluminum gallium arsenide (AlGaAs) matrix and monolithically integrated onto a silicon substrate. The QDs are obtained by a growth method that allows for the negation of a number of issues that are generally related to QDIP integration on silicon. Droplet epitaxy is a molecular beam epitaxy growth process designed expressly for the fabrication of compound semiconductor quantum nanostructures. The first step of this process is the creation of nanoscale reservoirs

**Figure 2.** (a) A schematic of the fabricated quantum-dot infrared photodetector (QDIP) on a silicon (Si) substrate. The bottom part of the structure consists of an n-type doped gallium arsenide (GaAs) buffer layer (red), which serves as the electron emitter. The absorbing part of the structure is made up of a 30nm thick aluminum gallium arsenide (AlGaAs, blue) barrier and six GaAs QD layers. A top n-type doped GaAs layer serves as the electron collector. (b) Atomic force microscope image of a layer of quantum dots grown by droplet epitaxy, showing a density of around \(10^{11}\) cm\(^{-2}\). (c) Scanning electron microscope image of the fabricated QDIP on silicon.

**Figure 3.** (a) Dark current density versus voltage characteristics measured at room temperature. (b) Mid-infrared photoresponse spectrum measured at 80K at 1V bias voltage.

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of metal atoms (Ga) on the substrate, in the form of nanometer-sized droplets. In the second step, each droplet is transformed into a QD. This step is performed by irradiating the substrate with a high flux of arsenic at relatively low substrate temperatures (around 150°C), thus promoting the incorporation of arsenic and the crystallization of the droplet into a GaAs island. The droplet epitaxy growth process delivers the high QD densities required for highly sensitive sensors and is compatible with CMOS technology. Using this method, QDIP-type devices with high efficiencies have already been demonstrated. The growth method also separates the fabrication of the photodetector from that of the CMOS sensor and related circuitry, allowing them to be realized in two separate steps while maintaining a monolithic approach.

In a QDIP pixel integrated on a 75mm silicon substrate, the bottom part of the structure consists of an n-type doped GaAs layer, which serves as the electron emitter (see Figure 2). The absorbing part of the structure is made up of a 30nm thick AlGaAs barrier and six GaAs QD layers with an overall areal density of around $5 \times 10^{11}$ cm$^{-2}$. A top n-type doped GaAs layer serves as the electron collector. The fabricated devices exhibit extremely low dark current densities at room temperature and a spectral response measured at 80K in the MWIR and LWIR ranges (see Figure 3), demonstrating the feasibility of QDIP integration on silicon.

In summary, we developed a QDIP for use in MSI devices using droplet epitaxy. This growth process enables the QDIPs to be integrated on silicon and may enable simultaneous, high-resolution detection of multiple wavelengths. We are currently working to develop a QDIP–Si multispectral pixel detector. This detector—able to read information coming from the VIS, MWIR, and LWIR spectral ranges in parallel—will be fabricated by monolithically integrating QDIPs onto a silicon substrate with an electronic readout.

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Author Information

Jacopo Frigerio and Giovanni Isella
L-NESS and Department of Physics
Politecnico di Milano
Como, Italy

Jacopo Frigerio is a PhD student. He works at the SiGe deposition facility and has co-authored more than 10 papers for peer-reviewed journals.

Giovanni Isella has been an assistant professor of condensed matter physics since 2003. He leads the SiGe growth facility and has co-authored more than 100 papers for peer-reviewed journals.

Sergio Bietti and Stefano Sanguinetti
Department of Materials Science
University of Milano, Bicocca
Milano, Italy

Sergio Bietti is a post-doc at the III-V growth facility at the L-NESS laboratories in Como. He has co-authored more than 30 papers for peer reviewed journals.

Stefano Sanguinetti has been associate professor of condensed matter physics at the department of materials science since 2004. He leads the III-V growth facility at the L-NESS laboratories in Como and has co-authored more than 150 papers for peer reviewed journals.

References


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