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ABSTRACT

Global shutter is a feature of some CMOS image sensors that allows capture of an entire image at a single point in time. We discuss how the device architecture of InVisage's QuantumFilm enables global shutter operation by controlling the bias on the device stack without an additional transistor, giving high shutter efficiency in a 1.1 μm pixel CMOS image sensor. We use drift-diffusion device simulations to inform our design and reveal device and material properties that are key for carrier selectivity. Based on our device model, we fabricated global-shutter-enabled QuantumFilm devices for near infrared sensing applications and present a characterization of our devices.

Keywords: quantum dot, CMOS image sensor, near infrared, global shutter, carrier selective contacts

1. INTRODUCTION

Global shutter is a feature of some CMOS image sensors that allows capture of an entire image at a single point in time. It is especially important for active illumination infrared sensing in outdoor settings, such as collision avoidance and iris and face recognition, because it aids the rejection of bright background light and reduces power consumption. Whereas conventional CMOS sensors achieve global shutter by adding an extra transistor to pixels of 3 μm or larger, InVisage's QuantumFilm enables a new type of global shutter that operates by controlling the bias on the QuantumFilm device stack. QuantumFilm is a proprietary semiconductor made from semiconductor nanoparticles, developed by InVisage Technologies for use in a 1.1 μm pixel CMOS image sensor.

The QuantumFilm device is a stack composed of several semiconductors, insulators and metals. The light absorption and photogeneration of electron-hole pairs is done by the QuantumFilm absorber layer, which is composed of a network of semiconductor nanoparticles, and acts in conjunction with interface and contact layers to allow the efficient extraction of that photocurrent. The completed device uses the QuantumFilm device stack on top of a silicon CMOS readout chip, where every pixel cell has a single electrical point connection to the QuantumFilm device stack.

In this paper, we discuss how the device architecture of QuantumFilm enables global shutter operation with high shutter efficiency. High shutter efficiency is particularly important in high dynamic range scenes where the "off" state must be achieved over a wide range of biases. Our approach uses specially designed carrier-selective layers in our device architecture.

We use drift-diffusion device simulations to inform our design and reveal device and material properties that are key for carrier selectivity. Based on our device model, we fabricated global-shutter-enabled QuantumFilm devices for near infrared sensing applications and will present a characterization of our devices. We demonstrate that QuantumFilm's global shutter operation offers a vehicle for achieving high-shutter-efficiency global shutter in 1.1 μm pixel CMOS image sensors.

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2. GLOBAL SHUTTER OPERATION USING QUANTUMFILM

Global shutter operation using QuantumFilm works by controlling the bias across the QuantumFilm to turn its photoresponse on and off at different points in time. Figure 1 shows a monochromatic external quantum efficiency (QE) vs. voltage curve (calculated from a current measurement vs. voltage) of the QuantumFilm device stack illuminated with 940 nm light. The light intensity used for the measurement was ~2 μW/cm^2. Three regions are highlighted in Figure 1. In Region 1 (1-3V), the QuantumFilm collects photocurrent with high efficiency, which is independent of bias. In this region, the QuantumFilm is “on” and photocurrent can flow out of the QuantumFilm to be collected in the sense nodes of pixels in the CMOS readout chip. The photoresponse is constant over a wide range of biases so that even as some pixel sense nodes collect photocurrent and their voltages change, the photoresponse of the pixels does not change. This gives the QuantumFilm device good linearity with respect to light intensities. The internal quantum efficiency in this region is near unity, so that the external quantum efficiency shown is due to the amount of light absorbed by the QuantumFilm. In the example curve shown in Figure 1 the quantum efficiency is ~31%, though other QuantumFilm devices currently achieve efficiencies of 42% at 940 nm.[1]

In Region 3 of Figure 1, the QuantumFilm has near zero photoresponse and is effectively “off”. As with the “on” region, there is a wide range of voltages (-0.5-0V) over which the QuantumFilm can be “off” with near zero photoresponse. This allows pixels with different voltages to all be “off” for a single common bias applied to the top electrode of the QuantumFilm.

Region 2 represents the transition between the “on” and the “off” regions of QuantumFilm operation, and is not used in global shutter mode.

In operating in global shutter mode, the bias applied to the top electrode of the QuantumFilm can be modulated in time to turn the QuantumFilm “on” and “off”, while the bias of electrodes at the bottom of the QuantumFilm can float with the sense node voltages of each pixel in the array. The QuantumFilm is turned “on” for some period of time to allow the pixels to collect photocurrent proportional to the intensity of light incident on each pixel. Following the “on” period, the bias on the top electrode of the QuantumFilm is turned “off” so that the photocurrent collection of all pixels stops. Because of the wide voltage range of the “off” region, all pixels can be effectively “off” even if they have different biases across them after collecting different amounts of charge during the “on” period.

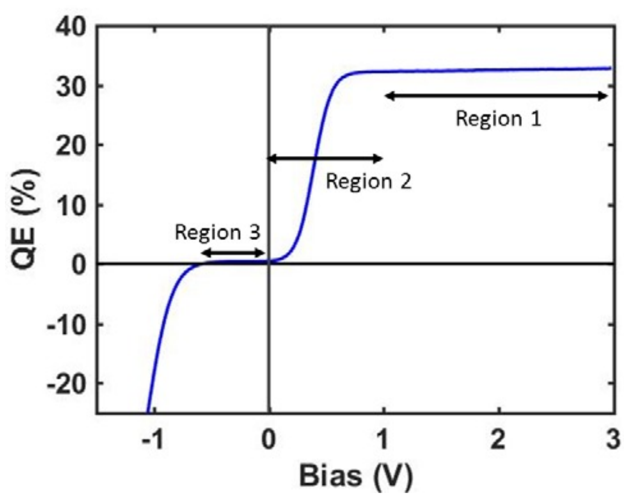

Figure 1: I-V curve showing external quantum efficiency for a wavelength of 940 nm vs. bias across the QuantumFilm. Three regions of operation are highlighted. In Region 1, where QuantumFilm is “on” (1V to 3V across the QuantumFilm), the QE is constant with applied bias. In Region 2 (0V to 1V), the QE falls off sharply with applied bias. In Region 3, where QuantumFilm is “off” (-0.5V to 0V), the QE is near zero.

3. OPERATING MECHANISM FOR GLOBAL SHUTTER USING QUANTUMFILM

Global shutter in the QuantumFilm device is achieved by designing the device stack to have collection asymmetry. When biased in one direction the collection of electrons at the bottom contact is easy, while when biased oppositely the collection of holes to the bottom contact is slow. In normal operation, when the QuantumFilm is “on”, the device is biased so that the bottom electrode is positively biased and the top electrode is negatively biased, driving electrons toward the bottom electrode and holes toward the top electrode. Thus when biased in Region 1 of Figure 1, photocurrent collection is highly efficient and the device is “on”, while when biased in Region 3, hole collection is slow so that most carriers recombine rather than being extracted and the device is “off”.

We used drift-diffusion device simulations in order to explore the device and materials properties that lead to high collection asymmetry. Simulations were performed using the software SCAPS[2], which is a steady state drift-diffusion semiconductor device simulator.

Figure 3 shows results of the simulations for different device stack parameters. The current voltage curves show a good correspondence to the experimentally measured curve shape under similar illumination conditions (Figure 1), indicating that the simulation input parameters correspond closely to the actual device properties.

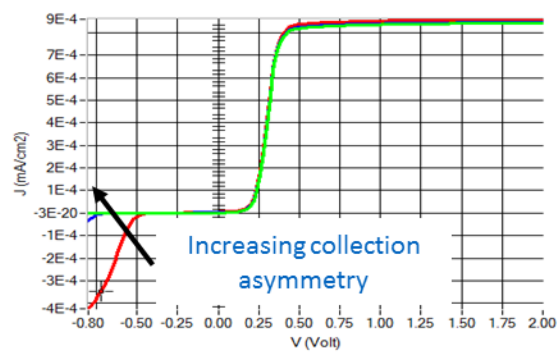

Figure 2: Simulated current-voltage curves for QuantumFilm devices with device properties. As the device asymmetry increases, the width of the “off” region expands toward negative voltages.

Figure 3 shows that as the device parameters are changed so that collection asymmetry increases, the width of the “off” region expands toward negative voltages. These simulations also show that it is possible to extend the width of the “off” region to be >1.0V without impeding collection of photogenerated charge during the “on” state.

4. APPLICATION OF QUANTUMFILM USING GLOBAL SHUTTER

One attractive application for global shutter operation is actively illuminated imaging in outdoor settings, where the active illumination must compete with bright sunlight. In such situations, global shutter allows for significant rejection of the background signal so that the active illumination can be more easily detected. Structured light is one example of active illumination, in which reflection of light emitted in a specific pattern is analyzed by image processing to determine the distance of objects from the camera. This method is often used by drones and autonomous vehicles for range sensing and collision avoidance, and by devices requiring 3-D mapping for industrial, medical, and entertainment-related applications (e.g. augmented and virtual reality).

With a traditional rolling shutter sensor, the structured light must be on for the entire frame time because the sensor is continuously capturing the image, leading to high power consumption. In global shutter operation, however, the structured light may be pulsed only during the “on” time of the QuantumFilm, leading to lower power consumption.

During the “off” period, the sensor is effectively insensitive to the background light. This pulse allows better rejection of sunlight irradiance and easier detection of the structured light.

An example of this is shown in Figure 4, which compares a silicon sensor in rolling shutter to QuantumFilm in global shutter operation in an actively illuminated outdoor setting. The scene is lit by bright sunlight, and the structured light is provided by a 940 nm VCSEL laser array. The silicon sensor operates in rolling shutter so that it is constantly integrating both bright sunlight and the structured light. As a result, the structured light is difficult to see on the objects in the background (car and building), which are at a distance of ~100 m. By contrast, the InVisage Spark4K sensor, which uses QuantumFilm in global shutter operation, collects light only during the “on” time of the device. In this example, the structured light is pulsed only during the “on” time, so that the average power consumption of the structure light laser is much lower. Because the QuantumFilm can be “off” during the remainder of the frame time, the background sunlight is only integrated for the time that the laser is pulsed. This enables the InVisage Spark4K image sensor to detect the structured light more effectively, especially when the structured light is comparatively dim, as it is on the car and building in this image.

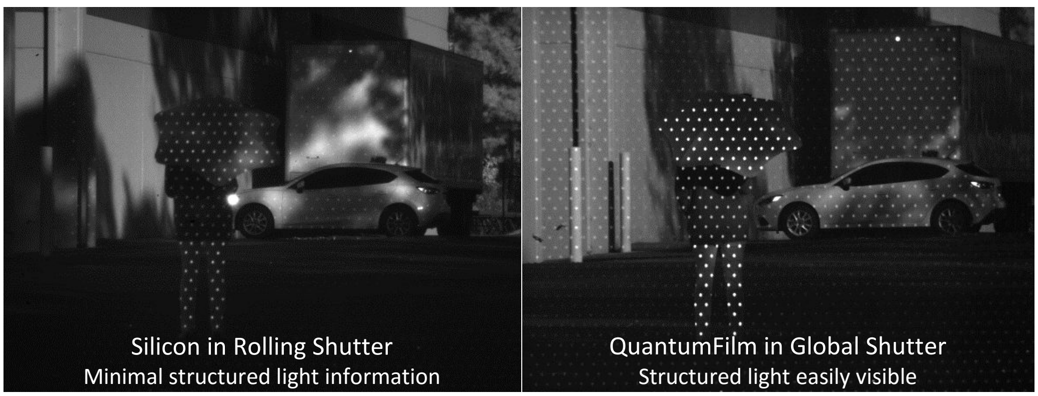

Figure 3: Left) A conventional silicon CMOS sensor with 1.1 µm pixels in rolling shutter with 70 ms integration time imaging an outdoor scene in bright sunlight and structured light provided by a continuous 940 nm VCSEL. The structured light is visible at close range on the person holding the umbrella, but is obscured by the bright sunlight on building and car in the background, which are at a distance of ~100 m. Right) InVisage Spark4K 1.1 µm sensor using QuantumFilm global shutter with 5 ms integration time (“on” time), imaging the same outdoor scene and structured light provided by the same 940 nm VCSEL, which is pulsed only during the 5 ms “on” time. The contrast and brightness of the two images have been adjusted to be the same for the background of the images, to correct for the difference in integration times and sensor responsivities. In the QuantumFilm image using global shutter, the structured light is easily visible even in the background.

It is also possible for silicon-only CMOS image sensors to operate in global shutter mode by the addition of an extra transistor per pixel. The additional transistor allows for “current steering” such that when the transistor is on, current is collected by the pixel, and when the transistor is off, current is blocked from the pixel. The disadvantage to this approach is that the pixel is typically larger to accommodate the additional transistor. Figure 5 shows a comparison of a 3 µm silicon-only CMOS image sensor operating in global shutter mode compared with InVisage’s 1.1 µm SparkP2, using QuantumFilm in global shutter. The InVisage sensor has much better spatial resolution due to its small pixel size, while both sensors are the same 1/7.5” format.

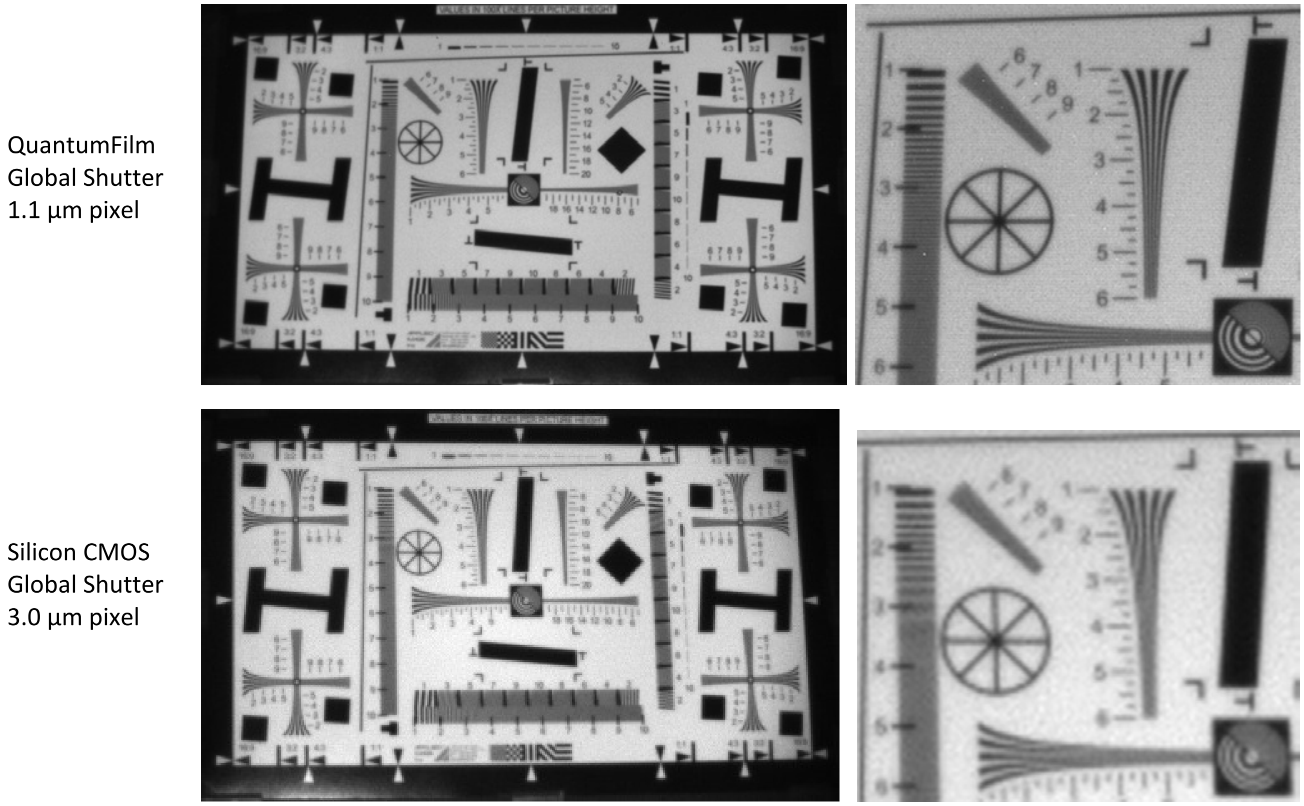

Figure 4: Top row) InVisage Spark P2 1.1 µm global shutter pixel imaging a resolution chart under pulsed 940 nm light. The smaller pixel size provides better spatial resolution. The right-hand panel shows a magnified view of the chart. Bottom row) A conventional silicon CMOS sensor with 3 µm global shutter pixels imaging a resolution chart under pulsed 940 nm light. The image has comparatively poor resolution and sharpness. The right-hand panel shows a magnified view of the chart.

5. CONCLUSION

QuantumFilm is a proprietary semiconductor device developed by InVisage Technologies, Inc. for use in a 1.1 µm CMOS image sensor. Its tunable band gap allows it to have excellent sensitivity to near infrared light, achieving external quantum efficiencies of 42% at 940 nm.[1] Its asymmetric device architecture allows it to operate in global shutter mode without the addition of an extra transistor. Global shutter operation is particularly important for outdoor imaging with active NIR illumination, where sensors need to reject background light. We have developed a theory for global shutter operation in QuantumFilm and used drift-diffusion simulations to explore ideal device architectures and materials properties. We demonstrate several applications of InVisage's image sensors using QuantumFilm's global shutter, and show how its higher sensitivity and spatial resolution provide superior near infrared imaging compared to competing technologies.

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