Light-Emission Crosstalk Model and Dynamic Correction Algorithm for Large-Scale SPAD Image Sensors

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Abstract—We present a new dynamic correction algorithm to suppress the impact of light-emission (LE) crosstalk in single-photon avalanche diode (SPAD) image sensors. The proposed algorithm demonstrated a capability of correcting both LE crosstalk and nonlinearity in a SPAD sensor, minimizing the effect of hot clusters and color shift that could potentially appear over the array. The results demonstrated a significant improvement in dark signal non-uniformity and color reproducibility. The proposed algorithm allows large-scale SPAD sensors to be implemented in various fields of imaging applications such as surveillance, biomedical and automotive.

I. INTRODUCTION

Single-photon avalanche diode (SPAD) image sensor provides a fully-digital 2D imaging solution, and is a promising candidate for a next generation of photon-counting image sensors for low-light and high dynamic range (HDR) imaging applications. A key challenge in high-definition SPAD cameras is the suppression of light-emission (LE) crosstalk that originates from electron-hole recombination around avalanche multiplication region. Pixel miniaturization leads to enhanced LE crosstalk, and it is thereby critical to mitigate the impact on image quality towards further scaling of the array. In recent decades, many studies have been conducted on the basic principle of LE crosstalk in SPAD arrays [1,2,3]. It has been observed that the spectrum of light emission contains a wide range of wavelengths from visible to near infrared. Unlike typical optical crosstalk and charge crosstalk discussed in CMOS image sensors, LE crosstalk observed in SPAD sensors can generate spurious counts not only to adjacent pixels but to distant pixels. Due to this unique property, there are several issues induced specific to SPAD image sensors. Fig. 1 shows a schematic representation of SPAD pixels with possible LE crosstalk contributions to adjacent pixels. LE crosstalk could cause enhanced hot clusters, increased apparent signal counts or dark counts, color shift, and reduced modulation transfer function (MTF), leading to image quality degradation. Nonlinear photoresponse of SPAD pixels gives additional complexity when estimating a magnitude of LE crosstalk over the array.

To mitigate the impact of LE crosstalk, several approaches have been proposed, including optimization and improvement of process, device, circuit and operation. An important countermeasure is to reduce the amount of LE crosstalk by introducing buried metal full trench isolation between pixels, to prevent emitted light to propagate from one pixel to another [4]. Another approach is the implementation of hot pixel elimination function into pixel circuits [5]. Alternative approach is to adaptively control a frequency of avalanche event through a modified recharging operation [6]. Yet, it is challenging for any of those approaches to thoroughly eliminate the effect of LE crosstalk. To minimize the image quality degradation, an appropriate correction method must be considered. To this date, a systematic method to correct the effect of LE crosstalk in the post-processing has not been presented.

In this paper, we propose a versatile correction algorithm for large-scale SPAD image sensors that suppresses the impact of LE crosstalk. A prototype megapixel SPAD array is used to examine the feasibility of this proposed algorithm.

II. PRINCIPLES & METHODS

A common approach to quantify the level of LE crosstalk is to introduce a crosstalk matrix; a spatial map of crosstalk probability. To obtain the crosstalk matrix for SPAD array, averaged dark frame is captured to extract addresses of isolated hot pixels. For each hot pixel, relative signal levels of the surrounding pixels are mapped around the extracted hot pixel. Based on each signal distribution created from the extracted hot pixels, a spatial map of crosstalk probability can be derived. Crosstalk count at the surrounding pixels is proportional to the signal count at the core hot pixel. This indicates that LE crosstalk contribution is predictable based on the core hot pixel level and the predefined crosstalk map.

Fig. 2(a) illustrates the isolated hot pixels using a synthetic dark image. Due to high reverse bias operation, SPAD image sensors tend to suffer from higher hot pixel population compared to CMOS image sensors. Fig. 2(b) shows an example of LE crosstalk matrix K, representing the crosstalk percentage from central to adjacent pixels. Fig. 2(c) shows the effect of LE crosstalk which can be represented by a convolution of Fig. 2(a) and (b). Each isolated hot pixel behaves as light emitting source to form a hot cluster. Fig. 2(d) shows the result of conventional hot pixel correction (HPC) based on a selective 1D median filtering. LE crosstalk-induced hot clusters spread over multiple pixels, and hence the conventional approach cannot fully eliminate the defective pixels.

To apply a precise correction to LE crosstalk, active recharging-based operation must be employed instead of passive recharging-based operation, where non-monotonic photoresponse precludes a unique estimation of crosstalk contribution. As one of the examples of active recharging, clocked recharging is conducted by providing a periodic recharging clock fed to a gate of recharge transistors [6]. In contrast to the conventional passive recharging, the clocked recharging-based sensor restricts the maximum photon counts per frame allowing to reduce power consumption, which makes it a viable option for megapixel resolution sensor suited for imaging applications.

Fig. 3(a) and (b) represents a cross-section, a pixel circuit, and a timing diagram of clocked recharging-based SPAD sensor; a photo-electron triggers avalanche multiplication which induces LE crosstalk to adjacent pixels. Fig. 3(c) depicts a relation between the number of detected avalanche events (N_{ct}) and the number of incident photons (N_{ph}) for active and passive recharging-based operations. In passive recharging, (N_{ct}) decreases at high-light condition. In clocked recharging, one recharging event allows only one avalanche event at maximum, leading to a nonlinear monotonic photoresponse.

Fig. 4 shows a signal conversion flow for the clocked recharging-based SPAD pixels in the presence of LE crosstalk. The number of LE events is equivalent to N_{ct}, and contribution of the secondary photons is fed back to N_{ph} in the adjacent pixels. This feedback process could induce higher-order crosstalk events, and complicates analytical formulation of LE crosstalk contribution. However, the correction algorithm for LE crosstalk can be simplified when the aforementioned crosstalk matrix K is introduced.

Fig. 5 shows an image processing flow of the proposed LE crosstalk correction algorithm. First, a raw image is converted to "Image A" through nonlinear correction function F^{-1}. In parallel, the same raw image is convolved with matrix K' to create "Image B", where matrix K' represents a contribution of the LE crosstalk, obtained by replacing the central element of matrix K with 0. "Image B" is subtracted from "Image A" to create "Image C", which shows the result of both nonlinear correction and LE crosstalk correction applied. Finally, "Image C" is converted to "Image D" through conventional HPC. The proposed correction algorithm for LE crosstalk is represented by a following equation:

$$I_t = F^{-1}(I_{raw}) - I_{raw} * K'$$

where I_{raw} is the initial raw image, and I_t is the reconstructed image. Benefit of this algorithm is that it can simultaneously correct nonlinearity and LE crosstalk-induced artifacts, such as hot cluster and color shift, irrelevant to light intensity distribution.

To evaluate the feasibility of the proposed algorithm, a variant of 3.2Mpixel 3D-stacked back-illuminated SPAD sensor is used, which has relatively higher crosstalk probability than those presented in a previous report [7].

III. RESULTS

Fig. 6 shows the results of conventional HPC and the proposed correction applied to a 100-frame-averaged dark image captured by the 3.2Mpixel SPAD image sensor. In contrast to the conventional HPC, the proposed algorithm shows a significant improvement in the dark signal non-uniformity. Fig. 7 illustrates the diagram of measured hot pixel population over the array in each image presented in Fig. 6. The hot pixel population (>50cps at 25□) of the proposed algorithm has been reduced by more than 6 times with respect to the conventional HPC method.

Fig. 8 shows the images obtained using a SPAD sensor with on-chip Bayer color filter in mid-light (top images) and high-light (bottom images) conditions. Fig. 8(a) shows raw images, representing their relative difference in light intensity. Fig. 8(b) and (c) show the result of nonlinearity correction applied, and the result of LE crosstalk correction additionally applied, respectively. Fig. 8(b) shows a color shift towards magenta, where a degree of shift is dependent on the light level. Fig. 8(c), in contrast, shows robust color reproduction for different light levels. This result indicates that the proposed correction algorithm can properly compensate LE crosstalk-induced nonlinear color shift.

IV. CONCLUSION

In this paper, a dynamic correction algorithm to reduce the effect of LE crosstalk is presented. The algorithm demonstrated a significant suppression of LE crosstalk-induced hot cluster and color shift, in the presence of nonlinear photoresponse. The proposed algorithm allows the implementation of multi-megapixel SPAD image sensors into various fields of imaging and sensing applications, including electronic industry, surveillance, biomedical and automotive.

V. REFERENCES

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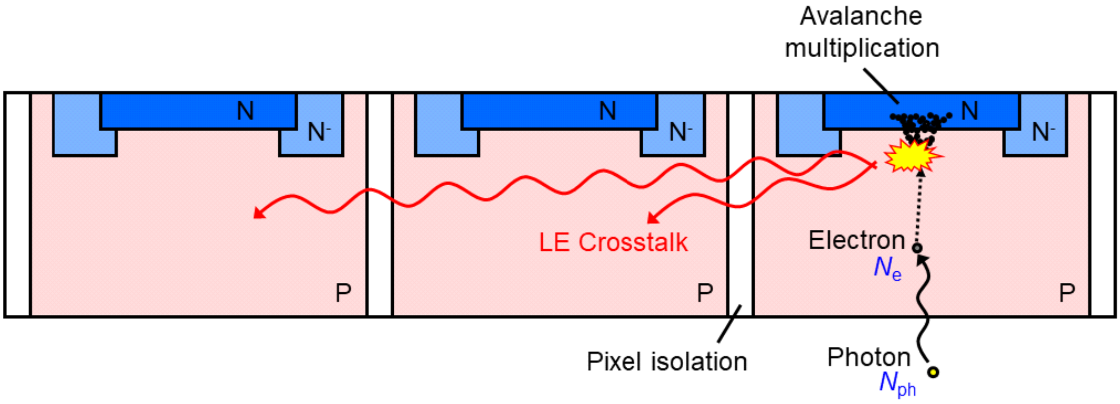

Fig. 1. Schematic representation of SPAD pixels and LE crosstalk contributions from one pixel to its adjacent pixels.

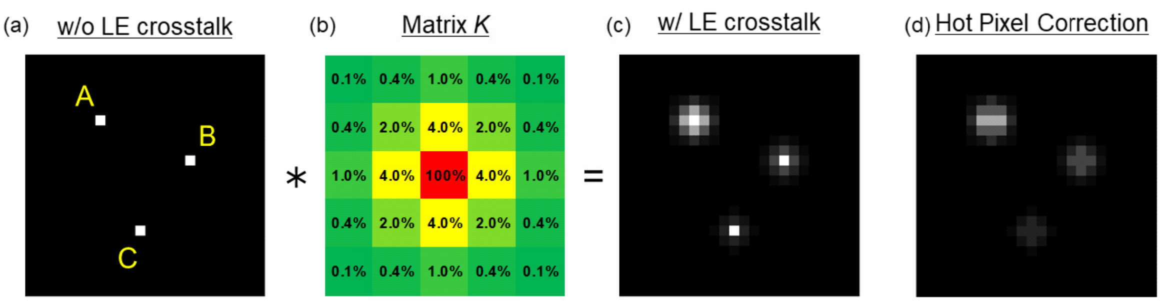

Fig. 2. Schematic views describing impact of LE crosstalk on image quality. (a) Synthetic image representing isolated hot pixels. (b) Conceptual example of 5×5 LE crosstalk matrix showing LE crosstalk percentage from central to adjacent pixels. (c) Synthetic image simulating the effect of LE crosstalk applied on (a). (d) Result of conventional hot pixel correction on (c) based on selective 1D median filtering.

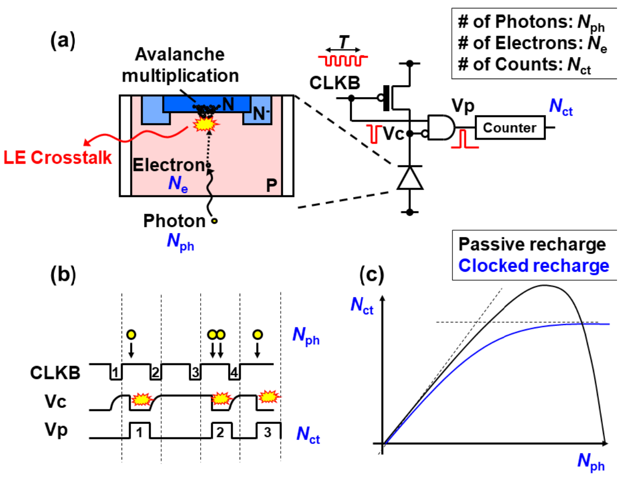

Fig. 3. Conceptual views of clocked recharging-based operation. (a) Cross-section and pixel circuit of SPAD pixel. (b) Timing diagram. (c) Schematic plot of relation between N_{ct} and N_{ph} for clocked and passive operations.

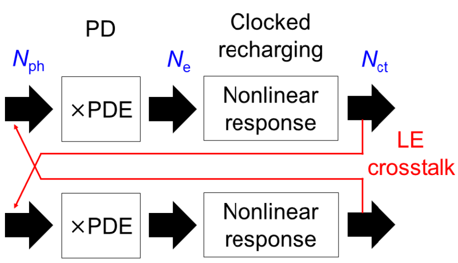

Fig. 4. Signal conversion flow for SPAD pixels in the presence of nonlinearity and LE crosstalk.

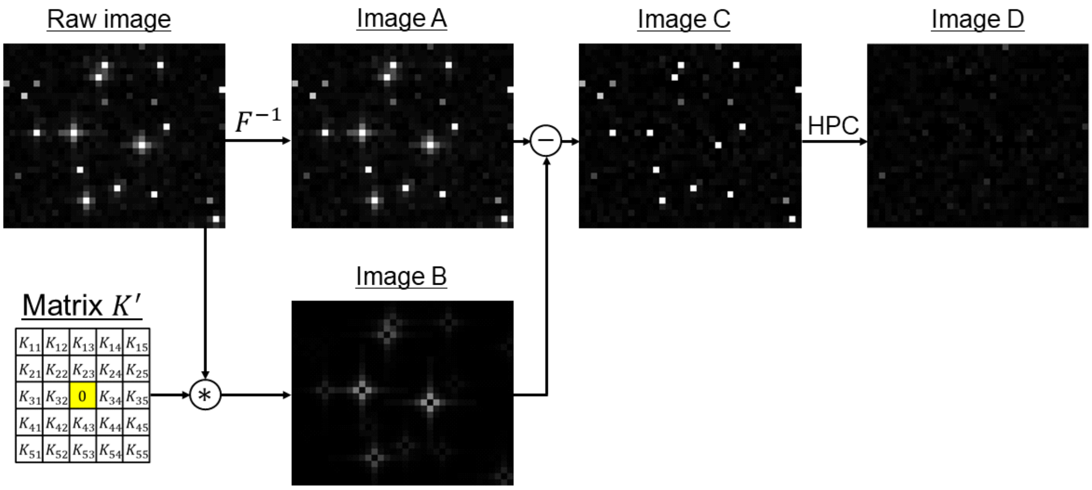

Fig. 5. Image processing flow of the proposed LE crosstalk correction algorithm.

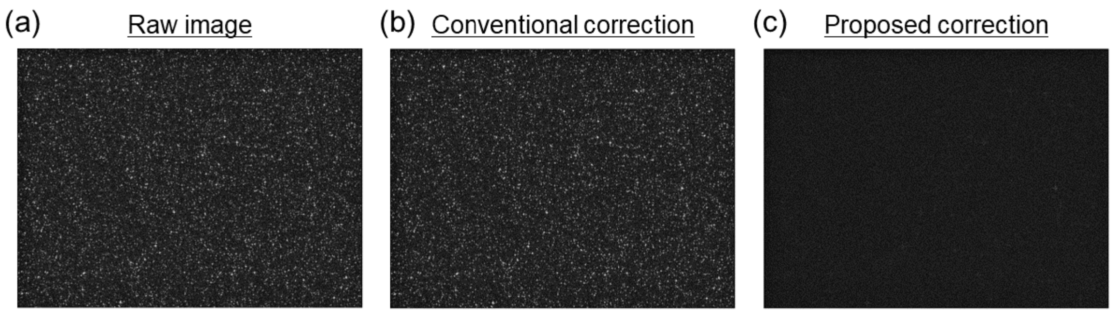

Fig. 6. Results of LE crosstalk correction. (a) Averaged full-resolution dark image captured by 3.2Mpixel SPAD image sensor. (b) Result of the conventional hot pixel correction. (c) Result of the proposed LE crosstalk correction.

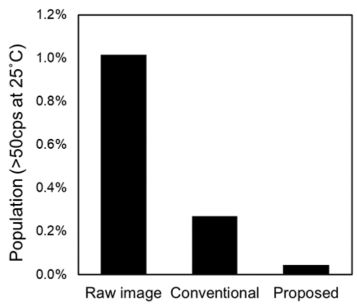

Fig. 7. Diagram of measured hot pixel population for raw image, conventional correction and the proposed correction.

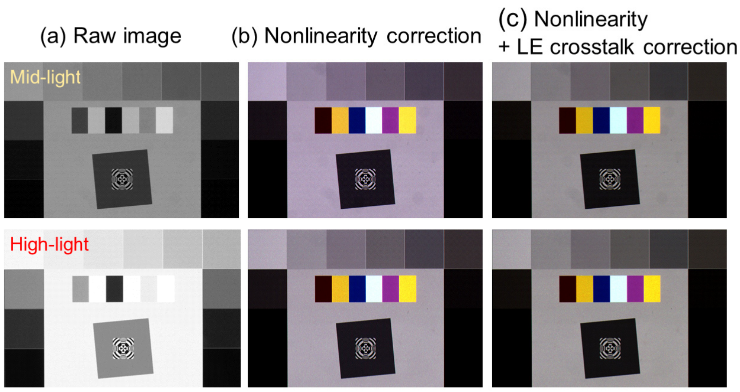

Fig. 8. Results of nonlinearity correction and LE crosstalk correction in color image under mid-light (top images), and high-light (bottom images) conditions. (a) Raw images captured by 3.2Mpixel SPAD image sensor. (b) Results of nonlinearity correction. (c) Results of the LE crosstalk correction simultaneously applied. Digital gain is applied to compare the color tone under equivalent contrast for (b) and (c).