SPAD-Array Photoresponse is Increased by a Factor 35 by use of a Microlens Array Concentrator

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Abstract: Using an array of 32x32 plano-convex microlenses, fabricated by co-polymer casting in a photoresist replica mold, we have been able to increase the detection sensitivity of a SPAD (Single Photon Avalanche Detector) array of 32x32 pixels, 50-μm pitch, up to a factor of 35.

 OCIS codes: (040.00040) Detectors; (040.1240) Arrays, (220.1770) Concentrators

1. Introduction

As it is well known, image detectors rarely incorporate on-board processing of the detected signal at the individual detector level (pixel), because the space taken by the circuit is lost to photodetection. Respect to a detector with spectral sensitivity σ (A/W), a fill factor $\eta=A_d/A_p$ of pixel area A_p (where A_d is detector area) reduces the apparent sensitivity to ση. As η may be small (e.g. 0.1), the on-board processing becomes impractical.

This issue is particularly true for the avalanche photodiode or SPAD (Single Photon Avalanche Detector), which requires a quenching circuit to recover from triggering after detection of single photons initiating the avalanche. Additional processing circuits that would be desirable to integrate along with the individual pixel for specific applications of arrays SPAD are: time sorters, time-of-flight rangefinders and spectrum analyzers, for applications in time-resolved spectroscopy, gene sorting and 3-D imaging [1].

Now, we may concentrate the power collected on a large pixel area A_p into a smaller detector area A_d, if the decrease in area is balanced by an equal increase of solid angle Ω, from input to output, to satisfy acceptance conservation [2]. The solid angle is $\Omega=\pi\ NA^2$, where NA is the numerical aperture of the field-of-view of receiver area. Thus, to get a high concentration ratio A_p/A_d we shall trade the numerical aperture NA^2_L of the lens imaging the scene. Frequently, the objective lens NA is limited by other considerations, like depth-of-focus, available size or weight, etc., so there is an ample range of recovery to be used for fill-factor improvement. Typical sizes involved in our SPAD design, based on a 120-nm technology, are: pixel size 50 μm by side, detector size 6 μm, number of individual SPADs 128x128. Thus we need an array of microlenses of 50 μm pitch and, using a lens diameter of 46 μm , the achievable fill-factor recovery (area ratio) is 59 (and 46 after the π/4 square-to-circle fill ratio).

2. Types of Concentrators

The optical element of the array may be a lens or a prism. Non-imaging prisms of different shape (cone, parabolic and tilted parabolic) [3,4] theoretically reach the highest values of concentration (100 and more) [5], but individual elements as small as 50 μm in diameters are difficult to figure on the required exact shape. Instead, plano-convex lens array are much easier to fabricate, because by thermal reflow a spherical dome is readily generated [7-9]. Concentration factors in the range of C=20 to 50 are achieved, adequate for a substantial recovery of fill-factor.

Before fabrication, we started assessing the concentration performance, using a computer ray-tracing subroutine to evaluate the concentration factor C of the plano-convex lens array, following ray trajectories across the lens down to detector and calculating C for NA from 0 to 0.4. As a typical result of simulations [6], the plano-convex lens attains theoretically a good C=45 at NA=0 and C=35 at NA=0.15 (corresponding to an objective lens F#=4), and also has an adequate depth of focus (about ±5 μm at focus distance =65 μm).

3. Experiment

A lens array was fabricated by the replica casting of a polymer into a photoresist mold, as described in Ref.[7]. A microphotograph of the array is shown in Fig.1. By a separate assembly operation, the array has been aligned and glued onto the silicon chip carrying the SPAD array. Size of the lens array is 1.6x1.6 mm, to match a 32x32 SPAD array with pixel size 50μm of our MEGAFRAME Project.

An optical bench has been used to test the lens arrays. It is made by a variable input-beam NA objective and a scanning CCD array interfaced to a PC. Results of concentration factor, measured on a typical sample of the fabricated lens array, along the Z-axis parallel to the optical axis of the lenses is shown in Fig.1 right, with NA as a parameter. Compared to theoretical value of 46 (at small NA), the measured concentration 37 is smaller, by a factor about 24%. Possible reasons, presently under investigation, are: defects at the spherical-to-plane edge of lens base; deviation from the spherical shape; residual scatter of the lens surface. Anyway, the obtained value is a good result, because it allows recovering of the same amount the quantum efficiency – no more penalized by the small area fill-factor, and this is the conclusion of this work.

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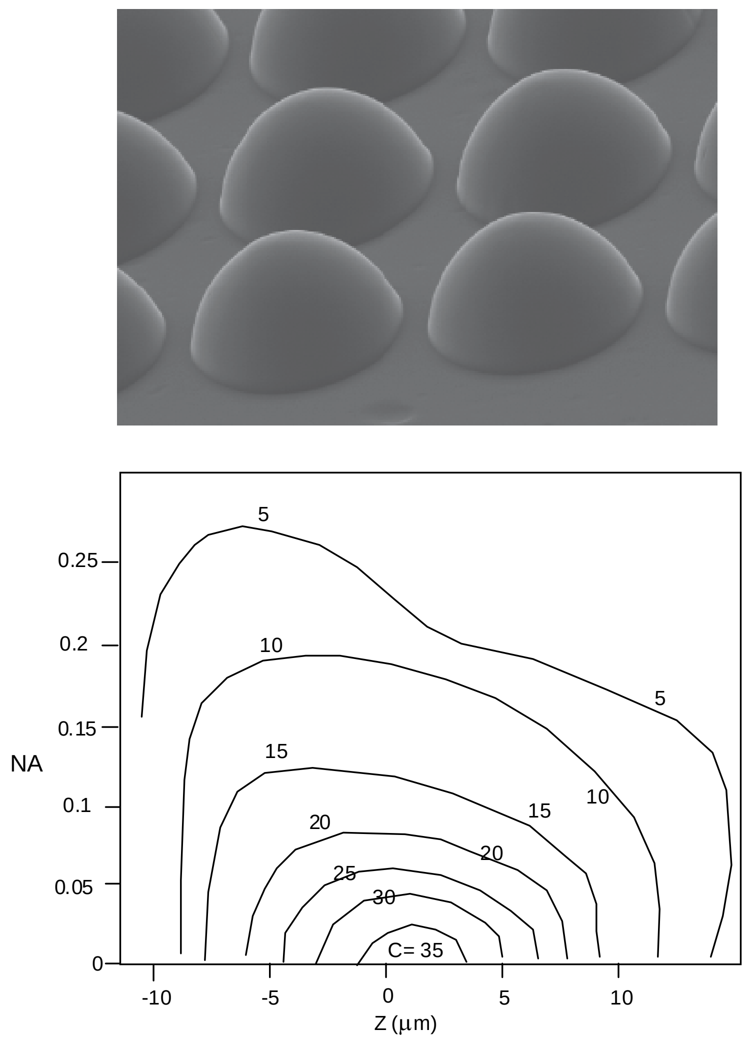

Fig.1 top: Microphotograph of the 128x128 elements, 50-μm pitch, plano-convex lens array fabricated by polymer molding (by courtesy of J.-H. Lee). Bottom: Measured concentration (the parameter labeling the curves) versus distance z along the optical axis, measured from the bottom plane surface (z=0), and versus NA of input objective lens. The measured data are specific for an individual lens in the array, but repeatability among different lenses of the same array is within ±5% error. Height of the spherical dome is 21.5 μm, focal length 37 μm.