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Nanoscale Photodetector Array and Its Application to Near-Field Nano-Imaging

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1. Introduction

Photodetector array have many applications, such as light detection and imaging. However, pixels in most photodetector array are micrometer scale or larger, which limits its application to relatively low spatial resolution detection. The possibility to realize photodetector array with pixel size at nanometer scale has become of great interest to various technologies. When the dimension of photodetector array's pixel is reduced to such a small scale, many new functions can be achieved. For example, with such a nanoscale photodetector array, it will enable us to image objects at a resolution better than that of conventional diffraction-limited imaging tool, for which the highest resolution that could be obtained is half of the illuminating light wavelength. Recently, many progresses on nanoscale photodetector array (NPD) have been made (Huang et al., 2001; Hayden et al., 2006; Yang et al., 2006; Maier et al., 2003), however most of them are based on nanotube technology and incapable of precisely controlling the position and configuration of detector array. It's desirable to have a photodetector array with nanoscale pixels while still having flexibility in device design and operation. In this chapter, we will present the research on such a photodetector array with nano-scale pixels based on dual side metal-semiconductor-metal (MSM) structure, including the design of NPD array, the simulation of NPD array's performance by finite difference time-domain (FDTD) method, the fabrication of NPD device, characterization of NPD array and the demonstration of nano-scale object imaging using the NPD array that fabricated.

2. Design of nanophotodetector array

The design of NPD array has a basic structure shown in Fig. 1. $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ternary material is chosen as absorbing material for near-IR (1.0-1.6 μm) wavelength range detection. A dual side MSM structure is employed, where the semiconductor active material is sandwiched by the top and bottom electrode. The top and bottom electrode stripes are perpendicular to each other, which enables the pixel addressing by NPD array. Concerns and considerations for these configurations are described under the following categories: (1) selection of active material and structure; (2) considerations in choosing MSM structure.

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Fig. 1. The schematic of the novel NPD array design, where Benzocyclobutene (BCB) fills all areas between NPD array pixels.

2.1 Selection of active material and structures

Commonly, GaAs material is used for 0.8 μm wavelength detection and has demonstrated a good performance (Biyikli et al., 2001; Biyikli et al., 2004; Seo et al., 1992). For near-IR (1.0-1.6 μm) wavelength range, typically $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, AlGaAs, InGaP and $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ are chosen as active material (Biyiklia et al., 2003; Chyi et al., 1994; DeCorby et al., 1997; Gao et al., 1994; Gao et al., 1995; Gao et al., 1997; Kim et al., 1998; Loualiche et al., 1990; Zhao et al., 2007). In practical application, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ternary compound is chosen as active material due to its band gap energy of 0.8 eV and lattice matching to InP material which has extensive applications in optical communications.

However, in near-IR region, the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ MSM photodetectors have not performed well. The primary difficulty is the low schottky barrier height (~ 0.2 eV) of commonly used Schottky contact metals on $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (Griem et al., 1990). Low barrier height results in excessive dark current and noise. One solution is to add an enhancement layer between the metal and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ absorbing layer to increase the Schottky barrier height. As a result, a Schottky barrier enhancement layer is used, i.e. digitally graded InAlAs/InGaAs super lattice (SL). The SL structure used is shown in Fig. 2. The graded super lattice consists of 3 periods of $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, whereby the first period is composed of 7 nm of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and 3 nm of $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, and the last period is reversed with 3 nm of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and 7 nm of $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$. The intermediary layer varies linearly between two endpoints in 2 nm increments. The graded SL structure is then capped with an additional 50nm $i\text{-In}_{0.52}\text{Al}_{0.48}\text{As}$ Schottky barrier enhancement layer.

2.2 Metal-Semiconductor-Metal structure

Metal-Semiconductor-Metal photodetector structure is equivalent to two Schottky diodes back to back, shown in Fig. 3. Their response is related to the current caused by the electron-hole pairs separated by the electric field in the depletion region of two Schottky diodes (Land et al., 1985). These devices usually have a simple planar design, often with interdigitated (IDT) fingers structure. The IDT MSM photodetector's respond speed is typically determined by the transit time rather than RC constant.

In practice, a dual side MSM structure is employed, where geometry with electrodes above and below a thin-layer of intrinsic semiconductor as active material is used for pixel

Fig. 2. Structure scheme of practical InGaAs active region with $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ Schottky barrier enhancement layer using digitally graded SL as transition layer.

Fig. 3. MSM structure photodetector is equivalent to two Schottky diodes back to back. addressing (shown in Fig. 4.). To detect a certain pixel, we will just connect to the right top and bottom electrode stripes. The detector where the top and bottom electrode stripe crosses will be the one that is sensed by the detector circuit. Thus, using $M+N$ stripes, we can address $M \times N$ pixels.

3. Finite-difference time-domain simulation of nanophotodetector array

In this section, highest possible resolution obtainable with the proposed imaging array shown in Fig. 4 is investigated using the finite-difference time-domain method. The FDTD method (Yee 1966) is one of widely used numerical techniques in simulations for various optoelectronic and photonic devices. However, due to the lack of proper active semiconductor model for photonics applications, conventional FDTD simulations are yet

Fig. 4. (a) 3D schematic for channelized NPD array, where the front electrode stripes have a crossing direction to the back side electrodes, forming a matrix for pixel addressing; (b) Top view of a 4 × 4 NPD array.

simple enough while still taking into account the physics of semiconductor materials. A new idea using multi-level multi-electron (MLME) semiconductor FDTD model has been developed by Huang and Ho (Huang 2002; Huang & Ho 2006), in which multiple energy band levels to describe the essential characteristics of the semiconductor energy band structures have been incorporated. This simulation scheme has also been successfully utilized in various photonic device applications with active semiconductors including photodetector, photonic crystal fiber, photonic transistor, whispering gallery resonator, and so on (Kim *et al.* 2008; Khoo *et al.* 2008). In order to understand the working mechanism of NPD array as a nanoscale imaging device, a MLME FDTD method has been adopted in this Chapter.

Fig. 5. Generation of photocurrent from photoelectrons in active semiconductor material. $\lambda=\lambda_a=1550$ nm is assumed, where λ and λ_a are the incident wavelength and resonant wavelength of the active semiconductor material, respectively.

In the FDTD simulations for the NPD array, photocurrent generated in semiconductor material by the incident light is one of key parameters in evaluating performance of a photodetector. The photocurrent generated in the active semiconductor medium is dependent on the incident (excitation) wavelength and the energy band gap structure of the semiconductor material. Conceptually, an active semiconductor material for photodetectors can be simplified as a medium with two different energy levels, in which the photocurrent can be calculated from the rate of excitation of ground state electrons from the ground level to the excitation level, which are subsequently returned back to the ground level via external electric circuit as shown in Fig. 5. In Fig. 5, electrons in ground state (level 1) are excited and transitioned to excited state (level 2), when the incidence wavelength is matched to inherent resonance wavelength of an active semiconductor material. Here, we assumed $\lambda = \lambda_a = 1550\text{nm}$, where λ and λ_a are incidence wavelength and resonance wavelength of an active semiconductor, respectively, which belongs to an optical telecommunication wavelength.

For conducting numerical simulations with the MLME FDTD code, the active semiconductor material needs to be spatially discretized as shown in Fig. 6, as well as other parts of the present device. The photocurrent generated in an active semiconductor material, which is composed of numerous FDTD pixels, can be quantitatively calculated from the following formula, which has been directly given based on the definition of the typical concept of electric current and photocurrent mechanism shown in Fig. 5.

$$I_{ph} = \frac{q}{t_{sim}} N = \frac{q}{t_{sim}} \left(\sum_{\text{pixel}} N_2 \right) \cdot N_{\text{density}} \cdot A \cdot h, \quad (1)$$

where $q = 1.6 \times 10^{-19} \text{C}$ is the electric charge, t_{sim} is the total time simulated, N_2 is the normalized number of electrons in the level 2 in a single FDTD cell, N_{density} is the number of electrons per unit volume, A is the area of the FDTD pixel, and h is the height of the NPD pixel. Here, we set $t_{sim} = 1.0 \text{ ps}$, $N_{\text{density}} = 0.563 \times 10^{22} / \text{m}^3$, $A = dx \times dy = 5 \text{ nm} \times 5 \text{ nm}$, and $h = 300 \text{ nm}$ considering a dimension for fabrication.

Fig. 6. Discretization of an active semiconductor material for the MLME FDTD method. Photoelectrons in each pixel are generated by light illumination. Photocurrents can be calculated with the photoelectrons.

Fig. 7. Simplified two-dimensional schematic illustration of the NPD array.

InGaAs is used as active semiconductor regions of the NPD array. A protective material such as benzocyclobutene (BCB) is filled between pixels to support device structures and form cladding layer to each pixel. Top and bottom electrodes are placed at front and backside of the array for the purpose of photocurrent pickup to external electric circuit to detect the photocurrent generated in each pixel of the NPD array. Bottom electrode could be either a transparent conducting oxide (TCO) or a thin metal layer for light passing through. The refractive indexes of InGaAs, BCB, and air at 1550 nm are assumed to be 3.4, 1.5, and 1.0, respectively.

Fig. 7 illustrates a simplified two-dimensional schematic of the NPD array for clearer description of its working principles for a practical photocurrent pickup mechanism. The active semiconductor material slabs, where photoelectrons are generated by the incident light as described in Fig. 5 and 6, are separated by protective material with lower refractive index that forms cladding layer to each NPD pixel and supports the device structure mechanically. The active semiconductor layer is sandwiched between the top and bottom electrodes. Top and bottom electrodes are placed at front and backside of the array for the purpose of photocurrent pickup to external electric circuit to detect the photocurrent generated in each pixel of the NPD array. Very thin layer of metal layer or optically transparent conductor such as transparent conducting oxide (TCO) will be used for the bottom electrode, forming a matrix with top metal electrodes for pixel-array addressing as shown in Fig. 4. In our NPD design, the active semiconductor region is made from InGaAs with refractive index of 3.4 and surrounded by BCB with refractive index of 1.5. In working condition, the active semiconductor materials in NPD pixels get excited by the near-field point-like light source, which will cause an increase of active material's conductivity and increase the electric current of detection circuit. Therefore, the photocurrent generated by each pixel is the signal of the NPD imaging device. If we define the width of NPD pixel as w and spacing between two adjacent pixels as s , the $w+s$ would be the resolution of the NPD array imaging. In our study, the $1/e$ (~36.79%) resolution criterion is used for NPD imaging characterization. If we assume the photocurrent generated by the m th NPD pixel as 1.0, when the generated photocurrent by the $(m+1)$ th or $(m-1)$ th pixel is less than $1/e$, we say the m th pixel and the $(m+1)$ th or $(m-1)$ th pixel can be distinguishable from each other. For

example, if the photocurrents generated in pixels 0 and 1 are 100 nA and 30 nA, respectively, we will have the ratio of 30% that is less than $1/e$. Then, these two pixels are distinguishable.

Fig. 8. The schematic of the NPD array with its dimensions for the FDTD simulation. Light to be detected is from the subwavelength metal slit. NPD pixels are labelled as 0, 1, 2, 3, and 4.

Fig. 8 shows a two-dimensional schematic illustration of the NPD array for our MLME FDTD simulations. The light of 1550 nm is incident from the bottom side. We assume a detector slab that is infinite in the direction perpendicular to the paper and the incident source has electric field polarization pointing along this infinite direction. The center-to-center distance between the NPD pixels is $w+s$ with a width of the NPD pixel of w and an inter-pixel gap of s , as same as in Fig. 7. The length of the NPD pixels is set to be $3.0 \mu\text{m}$ to investigate the optical power coupling between pixels, although in practical fabrication, the length of NPD pixels is only a few hundred of nanometers. The semiconductor fingers (pixels) play an important role in detecting incident field, which are converted into photocurrent via the mechanism shown in Fig. 5.

The placement of the imaging device to immediately proximate distance from the near-field light source within a few nanometer orders is strongly required to avoid rapid fading-out of the near-field light. Since all practical NPD devices will work in the near-field region of the illuminating light, the distance between aperture and the NPD array is set to be 10 nm, which assures that central pixels are within the near-field region of the light from aperture. To generate the near-field point-like source, we block the incident plane wave of 1550 nm by a metal film with a small aperture having a small width (a). The front side of the center pixel of the NPD array has been placed at very near distance away from the aperture, thereby, the NPD array can pick up the light from the aperture having diffraction-limited subwavelength light.

The photocurrents from the NPD pixels are obtained to explore the resolution of this novel NPD device for subwavelength diffraction limited imaging. One limiting factor is the optical

power coupling between adjacent detector pixels. The MLME FDTD simulation enables us to investigate such power coupling in the presence of absorbing media as well as the spatial distributions of electric field and photoelectron density.

Fig. 9. (a) Simulation of NPD array by conventional FDTD method. The NPD pixel is 200nm wide with 50 nm spacing. The highest resolution is 250 nm for 1550 nm wavelength; (b) simulation of NPD array by MLME FDTD method, the NPD pixel is 100 nm wide with 50nm spacing. The highest resolution is 150 nm for 1550 nm wavelength.

In order to investigate the effect of the optical absorption in optical energy coupling between adjacent pixels in the NPD array, both conventional FDTD and MLME FDTD models are used and results for both cases are compared with each other in Fig. 9. In conventional FDTD simulation, only optical energy in each NPD pixel could be simulated, where the light propagates in dielectric NPD pixels and no interactions between light and NPD detection region are considered. Simulation shows a highest resolution of 250 nm, shown in Fig. 9(a). On the contrary, in MLME FDTD simulation, both the optical energy and photocurrent generated in each pixel could be simulated. Before simulation, the number density of active semiconductor material in MLME FDTD model is calibrated to match real property of InGaAs semiconductor material to be used in experiments for 1550 nm wavelength. The calibrated active material loss of around $0.5/\mu\text{m}$ for a typical III-V semiconductor material, which is corresponding to a value $N_{\text{density}}=0.563 \times 10^{22}/\text{m}^3$ in eq. (1) as mentioned earlier. Shown in Fig. 9(b), MLME FDTD simulation shows a highest resolution of 150 nm, which is 100 nm (60%) higher than that by the conventional FDTD simulation. Compared with conventional FDTD model, the MLME FDTD simulation shows a better matching to the response of photosensitive material, which could be used to effectively simulate the photodetection process by the photodetectors.

In order to investigate the optical power coupling between NPD pixels, the average optical power in each pixel is calculated for the case of Fig. 9(b). Fig. 10(a) shows the electric field distributions, which indicates electric field is quasi-bounded by the center pixel (pixel 0) with subsequent coupling to the adjacent pixels (pixel 1, 2) and then to the next adjacent pixels (pixel 3, 4). Fig. 10(b) shows the corresponding photoelectron density of the whole NPD array from the electric field distributions of Fig. 10(a) with an arbitrary normalized linear scale, where most of the photocurrent is generated by the central pixel.

Fig. 10. (a) Electric field distributions and (b) corresponding normalized photoelectron density distributions obtained with MLME FDTD simulation in NPD array configuration. The dark red color indicates higher amplitude in arbitrary linear scale.

Fig. 11. Photocurrents generated in each NPD pixel.

Fig. 11 shows the photocurrents generated in each pixel from the spatial distribution of the photoelectron density profile of Fig. 10(b) by using eq. (1), where the photocurrent in each pixel for the 150 nm imaging resolution case, where the photocurrent generated in pixels adjacency to central pixel is less than 33% ($< 1/e$ criterion) of that in central pixel. The photocurrent in each pixel has been normalized to that in the central pixel. The estimated spatial resolution for this NPD array geometry is about 150 nm, which corresponds to a resolution of $\lambda/10$. The resolution of 150 nm by NPD array corresponds to about $\lambda/10$ for near-IR wavelength and about 25 times higher than the diffraction limited conventional imaging system in terms of imaging area.

The achieved optical resolution is substantially below the subwavelength diffraction-limit of $\lambda/2$, which can be potentially applied to the observation of nano-scale moving objects or living cells.

4. Nanofabrication of the NPD Array

4.1 Fabrication of NPD array

Several techniques to fabricate such a nano-imaging device have been developed to realize the 3-dimensional structure of NPD array, including BCB wafer bonding technique and metal oxide sol-gel based nanoscale direct patterning technique (B. Liu et al., 2008a, b). The pixel width and spacing of NPD array varies from 100 nm to 400 nm. A layer of Au/Ti (55 nm/5 nm) metal was deposited as receiving bottom electrodes. Up to 4×4 NPD array have been fabricated, where the smallest array pixel is as small as 100 nm wide with 100 nm spacing. Fig. 12(a) shows the top view of example 2×2 and 4×4 nanophotodetector array, where the bright electrodes are bottom receiving electrodes and the dark ones are front electrodes. An $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ based super lattice structure with 460 nm thickness is sandwiched between the top and bottom electrode stripes. The Au/Ti top and bottom electrode stripes are perpendicular to each other and form an addressable pixel array. Fig. 12(b) shows the detection region of a 4×4 NPD array, the pixel width is 400 nm wide with 400 nm spacing.

Fig. 12. (a) The top view of 2×2 and 4×4 nanophotodetector array, where the dark electrodes are front electrodes and the bright ones are back electrodes; (b) The detection region of a 4×4 NPD array.

4.2 Device packaging of nanoscale photodetector array

Packaging is of great importance for the characterization of photonic devices, especially when the size of devices is down to the nanometer scale. Since each NPD device only has a size no more than 1 mm × 1 mm square, to successfully cleave the NPD array into individual pieces the thickness of each NPD array device has to be at least 4~5 times smaller than the width of each NPD array device. Otherwise, the cleaving machine has to cut the device wafer deep in order to make a successful cleaving, which will easily cause the damage of the tiny NPD device and more debris during cleaving. Therefore, before cleaving, the whole wafer that carries the NPD array devices were polished down to ~150 µm thick.

In addition to cleaving process, bonding is also very important to the NPD device's performance. The quality of bonding will have a great influence on the electrical performance and thermal conductivity of NPD device, especially for devices as small as a few hundred nanometers. In practice, a silver paste is used to connect the NPD electrodes and extended electrodes. Fig. 13 shows the schematic of a bonded 4x4 NPD array using silver paste.

Fig. 13. The schematic of a bonded 4x4 NPD array.

5. Characterization and results

5.1 Photoresponse characterization

The electrical characterization of NPD array, which have pixel size of a few hundred nanometers, is different from micrometer scale MSM detectors. The primary reason is the small pixel size of NPD array. There are two main concerns on NPD characterization listed below:

- (a) The conventional planar IDT MSM structure photodetector has tens of or even more pixels working together, which leads to a large detection area of hundreds of square micrometers or even larger. As a result, it could generate relative large photoresponse signals of typically around microamperes level. On the contrary, in order to enable the pixel addressing function, each pixel in NPD array has to work individually. Since the NPD pixel has a size of a few hundred nanometers and detection area is only a fraction of square micrometers, the generated photoresponse signal by NPD pixel is very small. For instance, the estimated signal of a single NPD array pixel could be as small as tens of picoamperes. However, the advantage of NPD array pixels with small size is its corresponding low dark current.
- (b) Since the NPD array has pixel size of a few hundred nanometers, the corresponding detection area is only a fraction of square micrometers, which is already beyond the focusing limit of the optical objective lens used to focus the illuminating light onto the NPD

array. The large spot size onto the pixel array will inevitably cause errors in estimations of input illuminating light power.

To overcome above difficulties in NPD characterization, a high sensitivity Stanford Research DSP 830 Lock-In Amplifier was used to directly measure photocurrent generated by NPD pixel. Before the measurement using the lock-in, the instrument was calibrated using a Newport 818-IR detector head. The SR 830 lock-in shows an accurate current measurement of 2 pA, which already reached the detection limit of Newport 818-IR detector head. Therefore, the calibration shows the measurement system has a detection capability of larger than 2 pA, which is high enough for the NPD array's low photoresponse.

For the focusing light spot issue, however, there is no ready instrument available for such small light spot focusing. One solution is to use near-field scanning optical microscope (NSOM) system, where the light coming out from the NSOM scanning tip could reach such small size. Nevertheless, the throughput of the light out of the NSOM tip is as low as 10^{-6} for a 50 nm wide aperture NSOM tip. Considering the light coupling efficiency of at most 20% into the NSOM fiber, the throughput of a NSOM tip with 50 nm wide aperture is only on the level of 10^{-7} , which means that for an input optical power of 100 mW, output through a 50 nm aperture NSOM tip is only a few nW. If we use a larger NSOM tip, which has the size comparable to our smallest NPD array detection area, i.e. 100 nm square, the strong diffraction by the small size of NSOM tip aperture will cause large amount of light scattered into NPD array pixel surrounding materials of BCB and then into detection area of NPD array. In practice, a large focusing light spot by an objective lens is used to characterize NPD pixel photoresponse with only one NPD pixel is biased. The focused light spot is estimated to be 2 μm in diameter.

The schematic of the NPD photoresponse measurement setup is shown in Fig. 14. A He-Ne laser is used for the alignment of whole setup. The IR light source will be introduced by a foldable mirror. A high reflection coating filter is used as a beam splitter to direct the illumination light to the NPD device through a 50X objective lens. An IR-CCD camera is put right on the top of the beam splitter to monitor the position of focused light spot. The NPD sample will be fixed onto a 6-dimension adjustable stage for a good alignment to the focused light spot from the objective lens. The bias is applied by a Keithley 2400 Digital Sourcemeter through two probe stations. Stanford Research DSP 830 Lock-In Amplifier is series-connected to the power supply and NPD detection circuit and works in current mode. The output signal from lock-in is input to a Tektronix TDS3032B 300MHz oscilloscope and then collected by a GIPB data collection card through Labview.

To characterize the nano-imaging performance of NPD array, another measurement scheme using near-field scanning optical microscope (NSOM) system is shown in Fig. 15. A Nanonics MultiView 400 Near-Field Scanning Optical Microscope system is used to characterize NPD pixel. Except for a conventional setup for NSOM measurement, a SR830 lock-in amplifier and a Keithley 2400 Sourcemeter are added into the system. Then the output photocurrent signal of NPD device from the lock-in is sent to an auxiliary port of NSOM system, and photocurrent generated by NPD array pixel at each scanning position of NSOM will be recorded along with the scanning position. As a result, the whole system is converted to a near-field scanning photocurrent microscopy system, which is capable of topographical imaging, NSOM imaging and photocurrent mapping simultaneously.

Fig. 16 shows the photo response characterization of sample pixel for a 2×2 channel NPD array versus reverse bias. The wavelength of illuminating light is 1310 nm. The measurement shows a photocurrent of ~735 nA at 3.3 V bias, where the corresponding dark

Fig. 14. The schematic of NPD photoresponse measurement setup.

current is ~ 0.483 nA and more than 1000 times lower than the registered photocurrent. The corresponding responsivity is ~ 0.28 A/W and quantum efficiency (η) is 26%. The primary reason of relatively low quantum efficiency is due to the blocking effect caused by Au/Ti thin metal electrode for the receiving bottom electrode. The loss of $1.31\mu\text{m}$ light through a 20 nm thick Au/Ti (10 nm/ 10 nm) by simulation is still as high as 70%. The inset of Fig. 16 shows the calculated responsivity of NPD pixel versus reverse bias, where the highest responsivity registered is 0.28 A/W at 3.3 V bias.

5.2 Near-field Scanning Photocurrent Microscopy (NSPM)

To realize NPD array’s pixel addressable function, it’s necessary to individually characterize each pixel’s performance. However since each pixel of NPD array is nanometer scale, i.e. from 100 nm to 400 nm, it is difficult to characterize each pixel one by one. In this section, one way using NSOM system to qualitatively characterize NPD array and its nano-imaging performance is presented. Actually, one popular application of NSOM system is to illuminate the scanned surface in near-field region of the light coming out of the NSOM tip. Such application is typically used

Fig. 15. The schematic of NPD characterization setup based on NSOM system for photocurrent mapping measurement.

Fig. 16. Photocurrent of one 2x2 NPD pixel versus reverse bias. The pixel is 200 nm wide with 200 nm spacing. Inset, calculated responsivity of the NPD pixel at different bias.

in Biology to detect the fluorescence from single molecule or biological cell by illuminating them individually using NSOM tip. The region illuminated by NSOM tip only depends on the NSOM tip opening. Since NSOM probe tips' aperture generally varies from 50 nm to a few hundreds of nanometers, an illuminated region of 50 nm to a few hundred nanometer diameter circle is expected on the sample surface. To characterize NPD array using a NSOM system: (1) All electrical circuits should be connected and set up well; (2) A NSOM tip then scans the NPD array surface point by point. To obtain the image, the reflected or transmitted light is detected and recorded at each scanning point via a Photo Multiplier Tube carried in the NSOM instrument; (3) Simultaneously, the corresponding photocurrent generated by each NPD array pixel will also be recorded; (4) Imaging information and photocurrent at each scanning point are then integrated together using computer. As a result, one NSOM scan could generate both the physical imaging and the photocurrent map of the NPD array. By comparing the imaging and corresponding photocurrent map, one could characterize the effective pixel level resolution of the NPD array. The working mechanism of NSPM measurement is further shown in Fig. 17, where a 630 nm He-Ne laser is coupled to the NSOM tip to excite NPD array. In each measurement, one pair of NPD array electrodes, one from the top electrode stripes and the other from the bottom electrode stripes, is biased under 3 V. The NPD pixel at the crossing point of biased electrode stripes is the one to detect light signal from NSOM tip. The photocurrent generated by the biased NPD pixel is filtered and recorded while NSOM tip scanning the NPD array surface to generate the photocurrent map, which is also the image of NSOM tip by the NPD array.

Fig. 17. The schematic of near-field scanning photocurrent mapping measurement of NPD device to characterize the nano-imaging performance by NPD array. The NPD pixel at the crossing point of biased electrode is the one to detect signal.

The NPD pixel under measurement is from a 2×2 array with 250 nm wide pixels and 150 nm spacing. The generated photocurrent map by the biased NPD pixel is shown in Fig. 18. The two pair of dashed lines represent the position of the 2×2 NPD array electrode stripes, where the crossing points are the four NPD pixels. The depth of the color represents the

intensity of measured photocurrent generated by the biased NPD pixel, where the brighter the color the higher the photocurrent. The scanning area is $11\ \mu\text{m} \times 11\ \mu\text{m}$. The bright spot, shown in Fig. 18, in the 2D photocurrent map shows the image of the NSOM tip detected by the biased NPD array pixel. The measured FWHM diameter of the peak is $\sim 390\ \text{nm}$. This means the photocurrent generated by one NPD pixel will drop to less than half of the peak value when the light source moves to the middle position between two adjacent NPD pixels, which indicates this two pixels are distinguishable and the test NPD array has an imaging resolution of $390\ \text{nm}$. Since the imaging resolution of an imaging device could be defined as the sum of one pixel and one spacing, as a nano-scale imaging device the NPD array measured will have an imaging resolution of $400\ \text{nm}$, which well matches our experimental results. As a result, a near-field nano-scale imaging using NPD array has been successfully demonstrated.

Fig. 18. 2D photocurrent map generated by NPD pixel using home-made NSPM system, where the bright spot is the position of the biased NPD pixel with a FWHM diameter of $390\ \text{nm}$.

6. Conclusion

In summary, a novel nanoscale photodetector array, which could offer new functionalities that cannot be achieved by conventional larger scale photodetectors, is presented in this chapter. The novel design of the NPD array is described as follows: (1) NPD array is designed to have a dimension with nanometer scale, where the smallest pixel is only $100\ \text{nm}$ wide; (2) a vertical dual side MSM structure is used to enable pixel addressing; (3) the dimension of the NPD pixel detection area is specifically designed to form a wave-guiding structure to increase detection efficiency.

In addition, FDTD simulation of the NPD array is performed to simulate the photo detection and imaging performance of NPD array, where the photocurrent generated by the illuminated photodetector structure is investigated. The optical coupling effect between NPD pixels is explored by varying the width of NPD pixels and their spacing. Simulation results show that the MLME FDTD model has a good matching to the response of the photosensitive material, which could be used to effectively simulate the photodetection process by photodetectors. The smallest obtainable imaging resolution for $1550\ \text{nm}$ wavelength is $150\ \text{nm}$.

Finally, with several newly developed fabrication techniques, NPD array with up to 4×4 array size are successfully realized. The smallest NPD array pixel realized is 100 nm wide with 100 nm spacing. The sample NPD array pixel shows a photo responsivity of ~ 0.28 A/W and quantum efficiency (η) of 26% for 1.31 μm wavelength light. Using near-field scanning optical microscope, we characterized the nano-imaging performance of the NPD array fabricated. An imaging resolution of ~ 390 nm, which is $\sim 1/4$ the designed wavelength of 1550 nm, by NPD array has been successfully demonstrated.

7. References

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Research and development in modern optical and photonic technologies have witnessed quite fast growing advancements in various fundamental and application areas due to availability of novel fabrication and measurement techniques, advanced numerical simulation tools and methods, as well as due to the increasing practical demands. The recent advancements have also been accompanied by the appearance of various interdisciplinary topics. The book attempts to put together state-of-the-art research and development in optical and photonic technologies. It consists of 21 chapters that focus on interesting four topics of photonic crystals (first 5 chapters), THz techniques and applications (next 7 chapters), nanoscale optical techniques and applications (next 5 chapters), and optical trapping and manipulation (last 4 chapters), in which a fundamental theory, numerical simulation techniques, measurement techniques and methods, and various application examples are considered. This book deals with recent and advanced research results and comprehensive reviews on optical and photonic technologies covering the aforementioned topics. I believe that the advanced techniques and research described here may also be applicable to other contemporary research areas in optical and photonic technologies. Thus, I hope the readers will be inspired to start or to improve further their own research and technologies and to expand potential applications. I would like to express my sincere gratitude to all the authors for their outstanding contributions to this book.

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