FABRICATION AND CHARACTERIZATION OF AVALANCHE PHOTODETECTORS

BY

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THESIS

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ABSTRACT

Avalanche photodetectors are important for imaging applications because of their high sensitivity and low noise levels. For imaging applications, however, a two-dimensional array of APDs is required, and there are many fabrication issues involved in making such an array over a large area. In this work, fabrication and characterization of $32 \times 32$ arrays of InP (indium phosphide) based separated absorption, charge, and multiplication avalanche photodetectors (SACM APDs) is pursued to address the fabrication issues associated with making a high density array of APDs over a large area. Dark current and photocurrent uniformity of the array are characterized. Leakage current is also analyzed in terms of dark current and cross-talk by examining APDs with different mesa diameters and different separations, respectively. For these results, we find that the dark current of SACM APD devices mainly comes from the junction leakage. Thus, to reduce the dark current we need to improve the design of the epitaxial layers. This work also examines the dependence of cross-talk and the array packing density. A trade-off relationship is observed between the packing density of the devices and the leakage current.
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CHAPTER 1

INTRODUCTION

1.1 Motivation and Applications

Photodetectors (PDs) have been widely studied for telecommunication applications (Figure 1.1). To meet the data transmission demand for speed and capacity, the optical fiber network requires an optoelectronic device that converts a light signal to an electrical current needed on the receiver side. This photodetector has to operate at very high speed and be sensitive at 1.5 \( \mu \text{m} \) wavelength, so InP-based InGaAs separated absorption, charge, and multiplication avalanche photodetectors (SACM APDs) have been developed [4]. Figure 1.1 shows an example of a photodetector module for 100 G Ethernet. The photodetector chips are based on InP and are assembled into a fiber pigtail package.

![Photodetector Module](image)

Figure 1.1: Photodetector (PD) for telecommunication systems in a fiber pigtail package (from [1]).

Due to the characteristics of InP-based SACM APDs, they have also re-
ently been employed for three-dimensional (3D) imaging systems (Figure 1.2), active imaging systems, and navigation systems for landing vehicles in a remote environment. The SACM APD is very sensitive and has fast switching speed. These features enable the device to detect moving objects and to be used as a very sensitive detector. Thus, the APD device has been studied widely for imaging applications. Figure 1.2 shows an example of a 3D image taken by a light detection and ranging (LIDAR) camera, which is one application of APD arrays.

Figure 1.2: 3D image taken by LIDAR camera which has $128 \times 128$ pixel resolution (from [2]).

1.2 Previous Work

Early research on the InP based SACM APD adopted the mesa device structure [5]. However, the trend changed and the planar structure has been more recently developed. Even though the mesa structure is simple to fabricate, the reliability is believed to be improved with the planar structure. However, the planar type APD requires additional structures to reduce the electric field at the junction area, such as floating guard rings [6], etched diffusion well [7], or double diffused floating guard rings [8]. These structures require extra area, which is not suitable for close-packed high density two-dimensional APD arrays (Figure 1.3) that are required for imaging applications. Thus the mesa structure has advantages for APD array image applications [9]. Figure
1.3 is an example of a two-dimensional APD array that is designed for a LIDAR system. An important device goal of this application is achieving a uniform detector array over large area.

![Figure 1.3: 256 × 256 APD array over 1.5 cm² manufactured by OptoGration (from [3]).](image)

There are many fabrication issues associated with making two-dimensional APD arrays over a large area. This is because the current-voltage (I-V) characteristics of APDs are sensitive to the epitaxial layer thickness, doping concentration, or defects introduced during growth or device processing. Thus, non-uniformities in the epitaxial growth and processing result in significant variations in gain, dark current, and breakdown voltage across the array [10]. In addition, cross-talk, which is a leakage current component induced by the adjacent pixel, is also one of the major concerns for two-dimensional (2D) arrays. Thus for imaging applications these APD issues need to be studied [11].

### 1.3 Thesis Scope

This thesis discusses the fabrication and the characterization of InP-based SACM APD arrays. To be used for an imaging application, 32 × 32 arrays are designed, fabricated, and analyzed. We measure and report the uniformity and the cross-talk of the arrays. The dark current is also analyzed to determine the main source of the dark current. In Chapter 2, we intro-
duce the physical features of the SACM APD. The concept of the SACM APD derives from the semiconductor photodetector (PD). We first present the basic structure of the photodetectors, and then the avalanche photodetector (APD) concept is developed. Finally, we explain the SACM epitaxial layers and their requirements. The device structure and fabrication steps are described in Chapter 3. The epitaxial layers and the mask designed for this study are shown and followed by fabrication steps and details. The experimental setup and measurement results are presented in Chapter 4. We measure the dark current and photocurrent and calculate the gain. To check the uniformity of the $32 \times 32$ array, we measure the 32 devices down the diagonal of the array. The dark current and the cross-talk are also analyzed in Chapter 4. Finally, these results are summarized in Chapter 5.
CHAPTER 2
STRUCTURE OF PHOTODETECTOR

2.1 Semiconductor Photodetector

Figure 2.1 (a) shows a p-n junction diode under reverse bias which can be used as a photodetector (PD). At the junction region, the electrons from the n-type side diffuse into the p-side, and the holes from the p-type side diffuse into the n-side so the junction is depleted of charge carriers. Under reverse bias, the depletion region expands and current does not flow across the junction; thus there is no current under this condition. With the presence of incident photons of sufficient energy (Figure 2.1 (b)), however, electron-hole pairs are generated. Due to the applied external bias, the photogenerated electrons drift to the n-side and the holes drift to the p-side, which results in a current under reverse bias; this current is called photocurrent. Thus the current under reverse bias arises from photons that illuminate the device. Electron-hole pairs, however, can also be generated without light by other means such as tunneling and thermal generation. These carriers increase the noise factor because the carriers are generated even in the absence of light. This current is called dark current and should be minimized [12].

2.2 Avalanche Photodetector

An ideal photodetector creates one electron-hole pair per one incident photon (unity gain), so it is hard to detect low intensity light signals. To improve this performance, the avalanche photo detector (APD) was devised. The difference between the traditional photodetector and the APD is that the APD is operated under high reverse bias. The reverse bias enables the photogenerated carriers to accelerate under the applied field and collide with the
crystal lattice and to generate additional electron-hole pairs through impact ionization. These secondary carriers also gain sufficient energy to induce further impact ionization, which results in a generation of multiple electron-hole pairs, called avalanche gain [12]. Figure 2.2 shows these processes and how the APD generates multiple electron-hole pairs with one incident photon. The high electric field, however, also induces more leakage current from tunneling of carriers through the band gap. Since the leakage current from tunneling can also be multiplied by the avalanche effect, this leads to increased dark current.

2.3 Separated Absorption, Charge, and Multiplication Avalanche Photodetector

There are two processes that are needed for the operation of the APD. The first step is absorption of photons and the second step is the multiplication of charge carriers. Photon absorption occurs for incident photons with energy
Figure 2.2: An energy band diagram of APD describing the multiplication process of the photogenerated carrier by impact ionization and avalanche phenomena.

larger than the semiconductor band gap. However, narrow band gap materials have more leakage current due to thermal generation and because of tunneling from high electric field through the band gap. The device, however, needs to be under strong reverse bias in order for the avalanche phenomenon to take place. Thus, by separating the layers for absorption and for multiplication, we can optimize each layer for the operation of the APD. To moderate the electric field in both the absorption and multiplication layers, a charge layer is inserted in between these two layers. Figure 2.3 shows the biased energy band diagram design of the SACM APD which illustrates how the device reduces dark current due to tunneling compared to an ordinary APD [13].

Figure 2.4 shows the desired doping concentration, electric field, and energy band diagram. The electric field is given by

\[ E = \frac{qN}{\epsilon w_d} \]  

(2.1)

where \( q \) is the electron charge, \( N \) is the charge density of each layer, \( w_d \) is the depletion width, and \( \epsilon \) is permittivity [14]. As the Figure 2.4 shows, the absorption layer has a low doping concentration so the electric field, \( E \), is almost uniform through this layer. The charge layer, however, is highly doped, so \( E \) increases abruptly. Thus, the \( E \) of the charge layer reaches a
Figure 2.3: Layer schematics and energy band diagrams of ordinary APD and SACM APD to describe how the SACM APD reduces the dark current compared to the ordinary APD.

maximum at the end of the charge layer and this $E$ determines the electric field of the multiplication layer. Thus the charge density and thickness of the charge layer will control the electric field of the absorption and multiplication layers.
Figure 2.4: Doping concentration, electric field, and energy band diagram of the SACM APD. The doping concentration of the charge layer should be high and the thickness needs to be small. The electric field should be low for the absorption layer, but large for the multiplication layer.
CHAPTER 3

DEVICE STRUCTURE AND FABRICATION

3.1 Epitaxial Layers

The epitaxial materials used for the fabrication of the SACM APDs in this work were grown by nLight Corp., located in Oregon. Layers of different composition of InGaAlAs were grown on InP substrates. Figure 3.1 shows the design of epitaxial layers used for the SACM APD and a top view of the completed device by scanning electron microscope (SEM). Figure 3.1 shows the material composition, the thickness of each layer, and the desired etch depth which is approximately 3.5 µm. Figure 3.2 is the energy band diagram of the structure described in Figure 3.1 under zero bias, which was plotted using the SimWindow program.

3.2 Mask Design

To define the device features, we need optical lithography masks. A mask set was designed to study the uniformity of two-dimensional APD arrays, dark current, and carrier cross-talk. Figure 3.3 shows a unit cell of the mask. The unit cell includes a 32 × 32 APD array (total size of 3,262 µm × 3,262 µm), nine 3 × 3 arrays with different mesa diameter and array pitch, three 1 × 9 linear arrays with fixed mesa diameter but varying pitch, and one 1 × 8 linear array with fixed pitch but varying mesa diameter.

Two unit cells were designed because we fabricated the mesa structure using two different process conditions, one with only chemical etching and the other using a combination wet/dry etch. Thus, the arrays of the two different unit cells have slightly different dimensions due to the chemical etching process being isotropic and dry etching being anisotropic. The unit
Figure 3.1: Cross-section sketch of the SACM APD showing the material and thickness of each layer. To make the mesa structure, wet etching was performed to a depth of 3.5 $\mu$m. The top SEM view shows the ring metal contact and the sidewall around the device.

cell for chemical etching has extra space at the mesa edge to compensate for etching in the lateral direction. Figure 3.4 is a cross-section sketch of an APD pixel with the dimensions shown. For the mask design, the wet/dry combination pixel has 4 $\mu$m between mesa edge and top metal edge, but the wet etching pixel has 6 $\mu$m. The total etch depth is expected to be around 3 $\mu$m; thus the dimensions of the fabricated devices of wet etching and the combination etching are similar.

The mask set consists of a dark field mask for the top contacts and a light-field mask for the mesa features. The top metal is used to provide electric contact, and on the backside there is another metal contact which does not require a mask. For the chemically etched sample, the photoresist for the mesa structure was used directly as an etch mask. However, for combination etching, the sample requires a SiO$_2$ mask for dry etching because the dry etching process is operated at high temperature. Thus, the patterned photoresist is used to pattern the SiO$_2$ etch mask.

3.3 Dry Etching Fabrication

Due to the isotropic nature of the wet etch process, the packing density is limited. To pack the pixels more densely, we developed a combination wet/dry etch process as follows. For the patterning of mesas, SiO$_2$ was
Figure 3.2: Energy band diagram under zero bias plotted with SimWindow.
Figure 3.3: Sketch of unit cell of the APD array mask with description of elements.

Figure 3.4: Cross-section sketch of an APD pixel showing dimensions. (a) A pixel for chemical etching. (b) A pixel for the wet/dry combination etching.
Figure 3.5: Side views of a dry etched pixel (a) cleaved through a mesa to check the degree of undercut and (b) showing the vertical etched sidewall.

deposited on the top metal to approximately 400 nm thickness. AZ5214 photoresist was spun at 4000 rpm for 30 seconds, exposed, and developed with AZ327 MIF. The mesa SiO$_2$ mask was etched using CHF$_3$ plasma reactive ion etching (RIE) for 30 minutes. The photoresist was removed with acetone and O$_2$ plasma etching for 5 minutes. Mesa etching was performed using a short wet etch followed by dry etching. Before the wet etch process, photoresist was spun on the backside metal to prevent exposure to the etchant. Next the samples were put into H$_3$PO$_4$:H$_2$O$_2$:8H$_2$O for 2 minutes, which resulted in about 1.6 $\mu$m etch depth for each sample. After the wet etch process, the photoresist on the backside was removed and each sample was loaded into the inductively coupled plasma-reactive ion etch (ICP RIE) system. SiCl$_4$ and Ar gas were used with approximately 190 DC bias voltage for 5 minutes. The total etch depth after the two etch steps was around 3.9 $\mu$m. After the mesa etch, the oxide mask was removed using buffered oxide wet etching. The fabricated device is shown in Figure 3.5. Figure 3.5 (a) shows a side view of the wet/dry etched sample that was cleaved through a mesa to check the degree of undercut by wet etching. From this image we can verify that the undercut is around 1.5 $\mu$m as expected and the dry etched sidewall is very anisotropic. Figure 3.5 (b) shows the surface of the sidewall. It shows the anisotropic etch profile, but the sidewall surface is not as smooth as the sidewall formed by wet etching process alone.

The wet/dry combination etching is desirable due to its anisotropic profile, but the devices fabricated using the process had some problems. The removal
of the oxide mask after ICP etching attacked the APD epitaxial materials, resulting in removal of the top metal contacts. Moreover, the process of removing the SiO\textsubscript{2} dry etch mask using buffered oxide etch damaged the surface on the mesa top [15]. Thus, the APD array devices fabricated using chemical etching for the mesa structure were used for the characterization in the following chapters.

3.4 Wet Etching Fabrication

A backside contact consisting of 400 Å AuGe, 200 Å Ni, and 1200 Å Au is deposited first on the wafer under vacuum (pressure below $2 \times 10^{-6}$ Torr) using electron beam and thermal deposition. Next, for the patterning of the top metal contact, HMDS and AZ5214 were spin coated on to the wafer. After removing the edge bead at the sample edges, the samples were heated on a hot plate for 45 seconds at 110 °C, exposed for 27 seconds at 275 W power, heated on a hot plate again for 45 seconds at 110 °C, flood exposed for 15 seconds at 263 W power, and developed in AZ327MIF. The samples were then put into O\textsubscript{2} plasma at 300 W for 4 minutes followed by rinse in DI water. The p-type topside contact, consisting of 400 Å AuBe and 1500 Å Au, was deposited using electron beam and thermal evaporator. Metal liftoff was performed using acetone and the wafer was inspected under an optical microscope. To define the mesa structure, another lithography step was performed. The patterned photoresist was used as an etch mask for the mesa etch. Wet etching was performed with H\textsubscript{2}O\textsubscript{2}:H\textsubscript{3}PO\textsubscript{4}:H\textsubscript{2}O with a ratio of 1:1:8. The etch rate was 0.75 µm/sec and total etch depth was around 3.5 µm. These steps are summarized in the Figure 3.6. Figure 3.7 displays the side view of the wet etched mesa, which shows smooth surface and isotropic etch profile.
Figure 3.6: A flowchart describing the process steps to fabricate the wet etched SACM APD.

Figure 3.7: Side view of wet etched mesa.
CHAPTER 4

DEVICE CHARACTERIZATION

4.1 Measurement Setup

Using fabricated devices, current-voltage characterization was performed. Figure 4.1 shows the measurement setup. The SACM APD sample was placed on a position-adjustable probe station. A pin probe was used to make electrical contact to the top ring. The back side contact was connected to an Agilent 4156C semiconductor parameter analyzer (SPA). The SPA measured the current by sweeping the voltage ranging from -0.01 to 25 V in reverse bias and the data was transmitted to a computer workstation. A fiber pigtailed semiconductor laser with a center wavelength at 980 nm was used as the light source. The current for the laser was supplied by a Keithley 236 current source and the output power of the laser was calibrated by using a commercial photodetector. The laser was connected to a fiber probe and positioned over the mesa where the sample and stage of the probe station were observed by an IR camera.

4.2 Characterization

Dark current density and photocurrent density under two different incident optical powers, 0.255 mW and 0.729 mW, were measured and the gain of the photocurrent was calculated. Figure 4.2 shows the measured current density and the gain. The breakdown voltage occurred at around 23 V and the punch-through voltage was around 5 V at which the depletion region reaches to the n+ and p+ cap layer; thus the device is completely depleted. The abrupt increase of the photocurrent at around 3 V was due to the depletion region extending through the absorption layer. The dark current density
between the punch-through and the breakdown was between 0.05 and 10 nA and the photocurrent density was between 1 and 10 nA, which remained relatively constant over this range. The gain, $M$, was calculated by dividing the difference of photocurrent and dark current at a given reverse bias by the primary photocurrent ($M=1$) [10]:

$$M = \frac{I_{\text{photo}} - I_d}{I_{\text{pph}}}$$

(4.1)

where $I_{\text{photo}}$ is the photo current, $I_d$ is the dark current, and $I_{\text{pph}}$ is the primary photocurrent corresponding to the PD response, which is calculated by

$$I_{\text{pph}} = \frac{P_m}{hc/\lambda}(1 - R)(1 - e^{-\alpha d})$$

(4.2)

where $P_m$ is the power of the source light, $h$ is the Planck constant, $c$ is the speed of light, $\lambda$ is the center wavelength of the source light which was 980 nm, $R$ is the reflectance at the air and semiconductor interface (0.3), $\alpha$ is the absorption coefficient of In$_{0.53}$Ga$_{0.47}$As which was assumed to be 0.705 $\mu$m$^{-1}$, and $d$ is the thickness of the absorption layer which was 1.5 $\mu$m.
The current increased by a factor of approximately $10^9$ when the device was illuminated by the 980 nm laser. This indicates that the incident photons are inducing current. Note that different optical power levels create different amounts of photocarriers. These results confirm that the device functions as a photodetector.

Figure 4.2: Current density and gain as a function of reverse bias.

4.3 Uniformity

To check the uniformity of a $32 \times 32$ APD array with pixel separation of 100 $\mu$m, the dark current and the photocurrent under two different optical powers (255 $\mu$W and 729 $\mu$W) of the 32 pixels along the diagonal of the array were measured. The devices were chosen along the array diagonal from the top left to the bottom right as depicted in Figure 4.3.
Figure 4.3: 32 devices were measured along the diagonal of the $32 \times 32$ APD array.

Figure 4.4: Schematic of the adjacent two devices in the array. The designed dimensions (a) are different from the actual dimensions (b) because of isotropic wet etching process.
Figure 4.4 is a cross-section schematic of adjacent APDs in the array. The inside diameter of the top metal is 60 $\mu$m. The space between the outer edge of the top metal and the mesa edge was defined as 6 $\mu$m as displayed in Figure 4.4 (a), but the actual space turned out to be around 2.5 $\mu$m because of the isotropic wet etching (Figure 4.4 (b)). Figure 4.5 shows the I-V curve for the 32 APDs selected from the array. At the reverse bias of 20 V, the dark current was in the range of 0.73 $\pm$ 0.50 nA and the photo current was 229 $\pm$ 33 nA and 597 $\pm$ 77 nA for incident optical power of 255 $\mu$W and 729 $\mu$W, respectively.

4.4 Leakage Current Analysis

One of the reasons for the development of planar type APDs has been that mesa sidewall structures have potential for leakage current through the mesa surface [16]. However, the epitaxial layers can also contribute to leakage. Figure 4.6 shows the schematic of the dark current path. The orange lines represent the leakage current at the mesa sidewall and the blue lines indicate
the leakage current flowing through the epitaxial layers. To determine the main source of the leakage, the dark currents of APDs with different diameters (42, 62, 82, and 102 μm) were measured. The dark current was plotted as a function of area (junction leakage) and as a function of mesa perimeter (sidewall leakage).

Figure 4.7 shows I-V characteristics of APDs with different diameter. The plot shows a clear trend where dark current scales with the mesa diameter. To determine the dependence of dark current on junction area, the dark current was divided by the mesa area, yielding the dark current density.

Figure 4.8 (a) shows the current density as a function of mesa radius at 18 V reverse bias. The current density remains constant with radius, which indicates that the dark current scales with the cross section area. The dark current was also analyzed in terms of sidewall effects by dividing the current by the mesa perimeter. Figure 4.8 (b) shows the calculated result also at 18 V reverse bias as a function of mesa diameter. It shows a relatively linear dependence, which indicates that the mesa sidewall is not the dominant factor of the dark current. Based on these results we conclude that the dark current of this device mainly arises from the epitaxial layers of the device, rather than the etched sidewall. Thus the mesa structure could be a good candidate for a SACM APD two-dimensional array.
Figure 4.7: Dark currents of APDs with different diameters.

Figure 4.8: (a) Dark current of the mesa sidewall and (b) dark current density through the epitaxial layers.
4.5 Cross-Talk Analysis

Cross-talk is a primary concern for two-dimensional APD arrays for imaging systems [17]. When a pixel is illuminated, a few of the generated electrons can be collected by the neighboring pixels. These carriers would increase the dark current of the non-illuminated pixel, which induces an “image blooming effect.” This phenomenon is created by electronic cross-talk, and Figure 4.9 illustrates the concept.

![Cross-section sketch of the cross-talk phenomenon](image)

Figure 4.9: Cross-section sketch of the cross-talk phenomenon. Some carriers generated at the illuminated pixel are collected by the adjacent pixel.

To measure the cross-talk, a pixel was illuminated by a fiber laser at 980 nm wavelength with an incident power of 730 $\mu$W. The current of the neighboring pixels were then measured. The measurements were obtained from arrays of equal mesa size (the exposed area inside of the ring contact was 90 $\mu$m in diameter) but with varying separation distances between the mesas of 18, 30, 42, and 54 $\mu$m. Figure 4.10 shows the measured dark current of neighboring pixels on a linear scale. The cross-talk current at 18 V was taken and plotted as a function of distance between two pixels (Figure 4.11). The graph clearly shows that the cross-talk increases with decreasing distance between the two pixels. Thus, cross-talk can be reduced, but with the trade-off of decreased array packing density due to greater separation between the pixels.
Figure 4.10: I-V curve of a cell when its neighbor cell is illuminated.

Figure 4.11: The dark current as a function of the distance between two pixels.
A 32 × 32 InP-based separated absorption, charge, and multiplication avalanche photodetector array has been designed, fabricated, and demonstrated. The current-voltage curve of an individual device shows the characteristics of the APD device. In the presence of light, the current level of the APD increased and different powers of the optical source induced different amounts of photocurrent with a gain ranging from 1 to 10. The uniformity is one of the most important factors of the APD for the imaging applications; thus we fabricated and measured a 32 × 32 array which exhibited uniform distribution of dark current and photocurrent. To determine the main source of the dark current, the dark current of APDs with different diameters were measured and analyzed as a function of surface area and perimeter. Based on the results obtained, we conclude that the leakage current of the APDs were dominated by the junction leakage, rather than surface leakage through the mesa sidewall. Therefore, the mesa APD structure is comparable to the planar structure with the advantage of being able to achieve higher packing density in two-dimensional arrays. Another source for the leakage current is the cross-talk between adjacent pixels. The leakage of carriers increased when the pixels were closely packed. Thus due to cross-talk, there is a tradeoff in device performance between leakage current and packing density.
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