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6. AUTHOR(S)
Ming C. Wu
Tatsuo Itoh

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Los Angeles (UCLA)
Electrical Engineering Department
405 Hilgard Avenue, Los Angeles, CA 90095-1594

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13. ABSTRACT (Maximum 200 words)

The goal of the proposed research is to develop new photodetectors that are capable of high power operation at high frequencies for microwave fiber optic link applications. Conventional high frequency photodetectors have low saturation power because of the small absorption volume required to reduce transit time and parasitic capacitance. We have proposed a novel velocity-matched distributed photodetector (VMDP) that can achieve high bandwidth and high saturation power simultaneously.
During the performance period, we have successfully demonstrated three generations of long-wavelength VMDP's operating at 1.3 and 1.55 mm fiber optic communication wavelengths. The VMDP consisting of metal-semiconductor-metal (MSM) photodiodes serially connected by an optical core optical waveguide and an coplanar strip microwave transmission line that is velocity-matched to the optical waveguide. The MSM phodiodes have been patterned by both optical and e-beam lithography. We have demonstrated a bandwidth of 18 GHz and a quantum efficiency of 0.42 A/W. The maximum linear photocurrent measured is 12 mA. The distribution of photocurrents inside the VMDP has also been measured using a novel split contact structure. Test patterns on nanoscale MSM photodiodes show a bandwidth > 50 GHz (measurement limit).
The research results achieved in this program has been transferred to TRW, Focused Research, and BAE. TRW has provided additional funding for transfer the technology to TRW. Focused Research has obtained a Phase II SBIR to commercialize VMDP.

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[1] T. Chau, L. Fan, D. T. K. Tong, S. Mathai, and M. C. Wu, "Long Wavelength Velocity-Matched Distributed Photodetectors," IEEE Conference on Lasers and Electro-Optics, San Francisco, California, USA, May 3-8, 1998

[2] T. Chau, L. Fan, D. T. K. Tong, S. Mathai, M. C. Wu, D. L. Sivco and A. Y. Cho, "Long wavelength velocity-matched distributed photodetectors for RF fibre optic links," Electron. Lett. ,1998, 34 (No. 14), pp.1422-1424

[3] T. Chau, S. Mathai, A. Rollinger, D. L. Sivco, A. Y. Cho, D.C. Scott, T. A. Vang, M. C. Wu, and T. Itoh, " High Performance Long-Wavelength Velocity-Matched Distributed Photodetectors For RF Fiber Optic Links," in Conf. Proc. of the IEEE International Topical Meeting on Microwave Photonics (MWP'98), Sarnoff Corporation, Princeton, New Jersey, 12-14 October 1998, pp. 107-110

[4] A. Nespola, T. Chau, M.C. Wu, G. Ghione, C.U. Naldi, "Failure analysis of travelling wave MSM distributed photodetectors", IEDM 1998 - Technical Digest IEEE, 1998, pp.669-72.

[5] Nespola, A.; Chau, T.; Wu, M.C.; Ghione, G. Analysis of failure mechanisms in velocity-matched distributed photodetectors. IEE Proceedings-Optoelectronics, vol.146, (no.1), Feb. 1999. p.25-30.

[6] Nespola, A.; Chau, T.; Wu, M.C.; Ghione, G.; Naldi, C.U. Thermal runaway analysis for velocity-matched distributed photodetectors. GAAS 98. Conference Proceedings, (GAAS 98. Conference Proceedings, Proceedings of European Microwave Week, including GAAS98, 28th European Microwave Conference and MTT-S European Wireless 98, Amsterdam, Netherlands, 5-6 Oct. 1998.) London, UK: Miller Freeman UK, 1998. p.527-32.

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[8] Bo-Shiou Ke; Tai Chau; Yongxi Qian; Ming-Chiang Wu; Tatsuo Itoh (Edited by: Meixner, R.) Tapered slot antenna integrated with velocity-matched distributed photodetector. 1998 IEEE MTT-S International Microwave Symposium Digest , 1998. p.1241-4 vol.3.

(2) Scientific Personnel Supported by This Project

Ming C. Wu, Professor (P.I.)
Tatsuo Itoh, Professor
Tai Chau, Graduate Student Researcher
Noriaki Kaneda, Graduate Student Researcher

(3) Report of Inventions:

None.

(4) Scientific Progress and Accomplishments:

A. Introduction

The velocity-matched distributed photodetector (VMDP) is a novel type of travelling wave photodetector which can achieve both high power and high bandwidth, which are key parameters for high performance microwave fiber optic links. It was first proposed by Wu and Itoh in 1993 [1], and successfully demonstrated experimentally [2,3].

B. Objective

The primary goal is to develop a high power, high bandwidth photodetector for microwave fiber optic link applications at 1.33 μm or 1.55μm optical wavelength. The tasks include device design, fabrication, RF test, and high power failure mechanism investigation. Iteration of device design and fabrication to improve device performance is performed.

C. Device Principle and Structure

The schematic structure of the VMDP is illustrated in Figure 1. Active metal-semiconductor-metal (MSM) photodiodes are periodically distributed on top of a passive optical ridge waveguide. Optical signal is evanescently coupled from the passive waveguide to the active MSM photodiodes. The active photodiodes are designed to have very small optical confinement factor, keeping them bellow saturation under high optical illumination. The VMDP bandwidth is essentially limited by that of the individual photodiode, which can be very high, while its saturation photocurrent and overall efficiency can be high because photocurrent from each diode is added in phase through a 50 Ω coplanar strips (CPS) microwave transmission line that is velocity-matched to the optical waveguide. The MSM photodiodes serve two functions: generating photocurrents, as well as providing the periodic capacitance loading needed for velocity matching. The VMDP design allows the passive waveguide, the active photodiodes, and the microwave coplanar strips to be independently optimized.

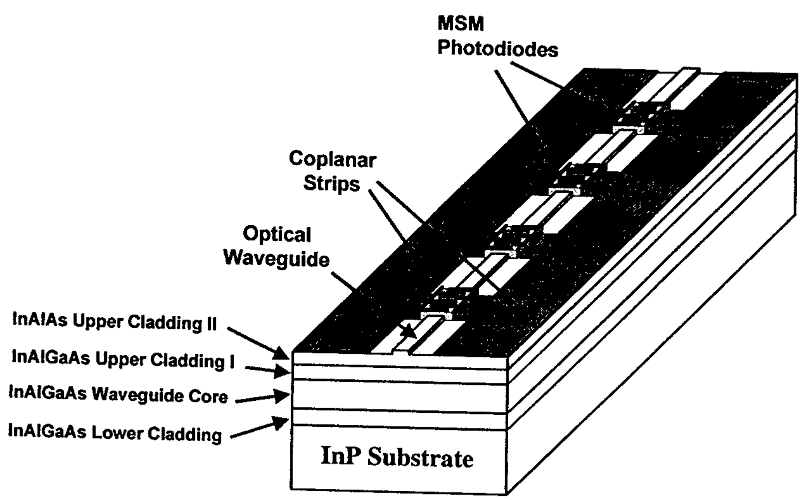

Figure 1. Schematic structure of long-wavelength Velocity-Matched Distributed Photodetector (VMDP)

The cross section and epitaxial layers structure of VMDP is shown in Figure 2. All epi layers are intrinsic, and grown lattice matched on semi-insulating InP substrate. The epi layers of the passive optical waveguide are transparent to 1.3 μm and 1.55 μm wavelength. The fabrication process has been discussed related publications [see section G and H]

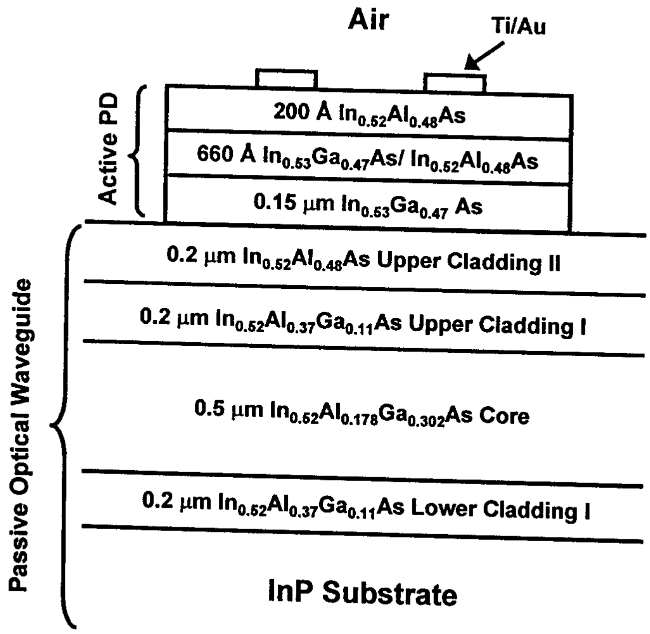

Figure 2. Cross Section of Velocity Matched Distributed Photodetector (VMDP). The Graded Superlattice consists of 11 pairs of alternate layers of $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ with thickness gradually varied in opposite directions from 55 Å to 5 Å with fixed period of 60 Å as shown.

The Schottkky barrier enhancement layer is employed to reduce dark current, and the graded superlatice helps reduce carriers trapping effect. Figure 3 shows the schematic band diagram of the device.

- **Band Diagram**

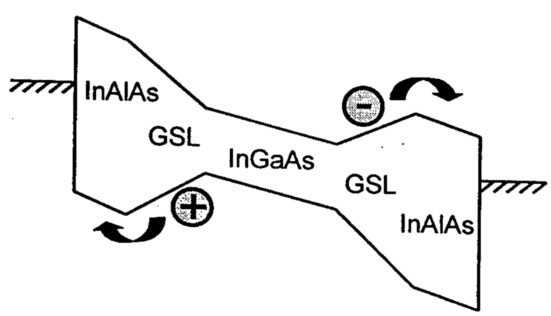

Figure 3. Schematic band diagram of active photodiode region

D. Result and Discussion

Three design iterations of VMDP have been fabricated and tested. All designs share the same epitaxial layer structure. The principle of operation of VMDP has been discussed in detail in [1-3]

D1. First Generation VMDP

D1.1 Objective

The main objective of first generation long wavelength VMDP is mainly to demonstrate the capability of InP-based long wavelength VMDP. It serves as a proof of concept for wafer and device design, fabrication technology, failure mechanism study, and possible improvement for future design.

D1.2 Approach

The first generation VMDP employed an array of 11 μm long, 48 μm wide MSM photodiodes, serially connected by a passive optical ridge waveguide with 3 μm width, 0.1 μm ridge height. Photocurrent generated by each diode is collected by a 50Ω CPS microwave transmission line. The CPS has 90 μm wide electrodes, and 30 μm spacing between electrodes. The MSM fingers have 1 μm finger width and 1 μm finger spacing are defined by optical lithography.

D1.3 Result and Discussion

We have experimentally demonstrated a long wavelength velocity-matched distributed photodetector (VMDP) with twelve metal-semiconductor-metal photodiodes. A 3dB bandwidth of 18 GHz and an external quantum efficiency of 0.42 A/W have been achieved. All devices exhibit linear responsivity up to 12mA DC current, limited by thermal damage of the MSM photodiode.

The finished devices are cleaved and mounted on copper heat sinks before testing. The VMDP exhibits very low dark current: 190 pA at 10 V bias for individual photodiode (11x48 μm^2), and 25 nA for the 1.2-mm-long VMDP with 12 photodiodes. The excess dark current in the VMDP is attributed to the leakage current under the CPS electrodes, which has much larger area than the active photodiodes. This can be eliminated by placing the electrodes on thin dielectric. The external quantum efficiency is measured to be 0.42 A/W after anti-reflection (AR) coating. The dominant loss comes from the coupling from optical fiber to the VMDP. All devices exhibit linear responsivity up to 12 mA of photocurrent.

The microwave performance of the VMDP is measured by HP 8510C network analyzer. The microwave return loss (S_{11}) is less than –22 dB from 0.1 to 40GHz. The characteristic impedance of the VMDP is matched very well to 50Ω (within 4%) for the entire frequency range. The frequency response of the VMDP is characterized by optical heterodyne method [4,5] using two external cavity tunable lasers at 1.55 μm. The optical signals are combined by a 3dB coupler, and coupled to the VMDP through a fiber pickup head. The output microwave is collected by a 50-GHz picoprobe (GGB Industries) and monitored by an RF power meter. The calibrated frequency response of the VMDP is shown in Figure 4. A 3dB bandwidth of 18 GHz is measured.

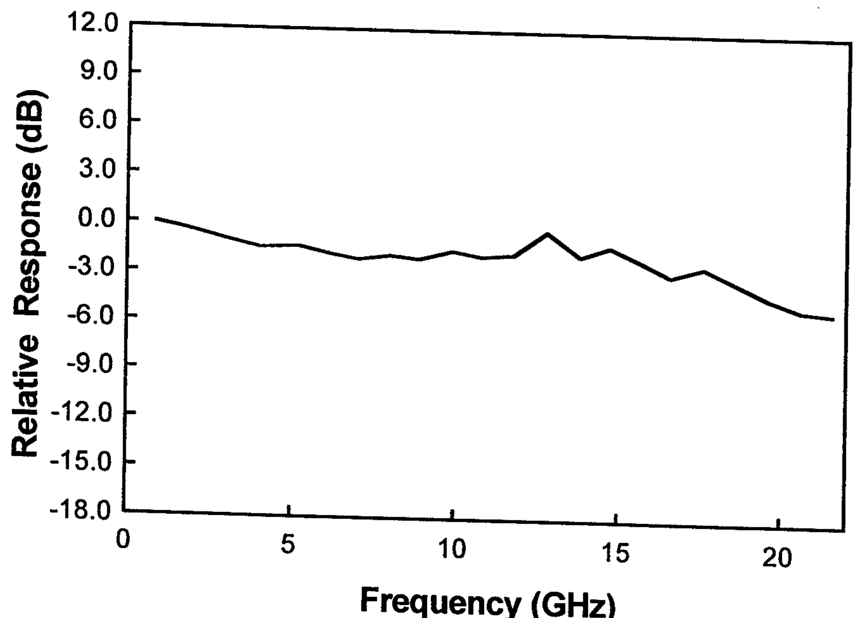

Figure 4. Measured Frequency response of long wavelength VMDP (12 photodiodes, total length = 1.2 mm)

Thermal studies were performed to determine the failure mechanism, a detail discussion can be found in [6]. The two important failure mechanisms studied were (i) thermal runaway due to increasing thermionic emission from positive feedback mechanism at high temperatures and (ii) avalanche breakdown in the depletion region of the detector leading to failure. A physics based quasi-3D coupled opto-electronic model has been implemented and simulation carried out to investigate the failure mechanism leading to catastrophic damage in InP-based VMDP. Destructive high current test reveals gold diffusion into semiconductor, thus suggesting the main failure mechanism is due to Schottky barrier dark current increase and related positive thermal feedback rather than avalanche breakdown. Improving the diffusion barrier of the Schottky contact should lead to higher photocurrent.

D2. Second Generation VMDP

D2.1 Objective

The main target of the second generation VMDP is to achieve higher saturation photocurrent, increase external quantum efficiency by reducing coupling loss from optical waveguide to active MSM photodiode.

D2.2 Approach

Compare to the first generation VMDP, we have made three major changes: (1) mesa width reduction to reduce optical coupling loss from optical waveguide to active metal-semiconductor-metal (MSM) photodiodes; (2) nitride passivation on mesa sidewall and underneath the large CPS metal contacts to reduce dark current and improve device reliability; and (3) the use of platinum in Schottky metal contacts to prevent gold diffusion at high power operation

D2.3 Result and Discussion

Improved performance of InP-based long wavelength VMDP with MSM photodiodes is experimentally demonstrated. A 3-dB bandwidth of 13 GHz and an external quantum efficiency of 0.57 A/W have been achieved. The VMDP exhibits very low dark current: 8.3 nA at 10V bias for a 1-mm-long VMDP with 13 photodiodes.

Item (1) and (2) are supported by experimental data. Compare to the first generation device, the second generation VMDP exhibits higher responsivity and lower dark current. However, the maximum saturation current is only 4mA compare to 12mA for the first generation VMDP. This is probably due to the difference in quality of the wafers used in each run.

D2.4 Split Contacts Structure

A split contacts test structure is included in the second iteration to investigate the photocurrent distribution along the VMDP. Figure 5 shows a top view schematic of the split-contact test structure.

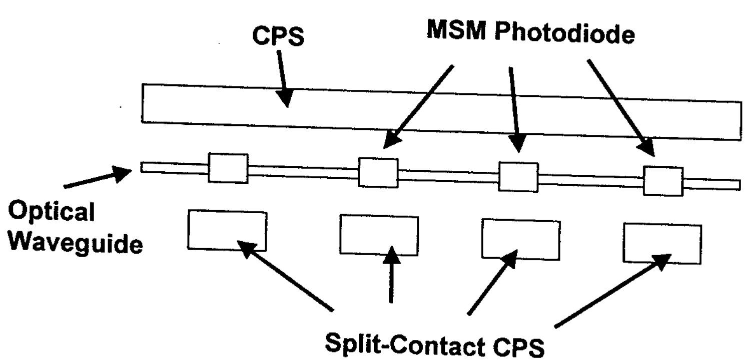

Figure 5. **Top view schematic of split-contact VMDP**

The test device consists of 10 MSM photodiodes, each with mesa width and length of 7 μm and 18 μm, respectively. Spacing between diodes is 58 μm. The optical ridge waveguide is 3 μm wide, and CPS metal strip width is 90 μm and 25 μm gap between strips. From theoretical calculation, we expect a responsivity of 0.1 A/W per diode. However, we observed that most of the light got absorbed in the first diode, with a responsivity of 0.25 A/W. Compare to the standard VMDP with continuous CPS with typical responsivity of 0.4 A/W, this indicates more than 50% of current is generated by the first diode. From the experimental finding and BPM simulation results, it is clear that the most important change is to redesign the optical waveguide. A proposed approach is to etch the waveguide deeper, through the core layer, to provide a stronger lateral waveguiding.

D3. Third Generation VMDP

D3.1 Objective

The third iteration of VMDP mainly focuses on achieving bandwidth beyond 20GHz.

D3.2 Approach

Submicron MSM fingers photodiode using electron-beam writing is used to achieve higher bandwidth. Although BPM simulation result indicates a good waveguide structure requires the mesa and waveguide width to be same, a large mesa was used so that the MSM fingers sit entirely on the mesa to avoid breakage if fingers run across the mesa sidewall step. In principle, transit time limited bandwidth in excess of 100GHz is expected for submicron MSM photodiode.

D3.3 Result and Discussion

In October 1998, we have successfully fabricated VMDP with submicron MSM fingers of 0.3 um finger width and 0.2 um finger spacing. The fingers were done by electron beam writing at Cornell. S-parameter measurements show very good 50 Ohm match, however, heterodyne frequency response measurement shows that device bandwidth is well bellow 10 GHz. We further study this with pulse response measurement with an ultrashort pulse from a mode-locked fiber laser. Figure 6 shows the schematic of the measurement setup.

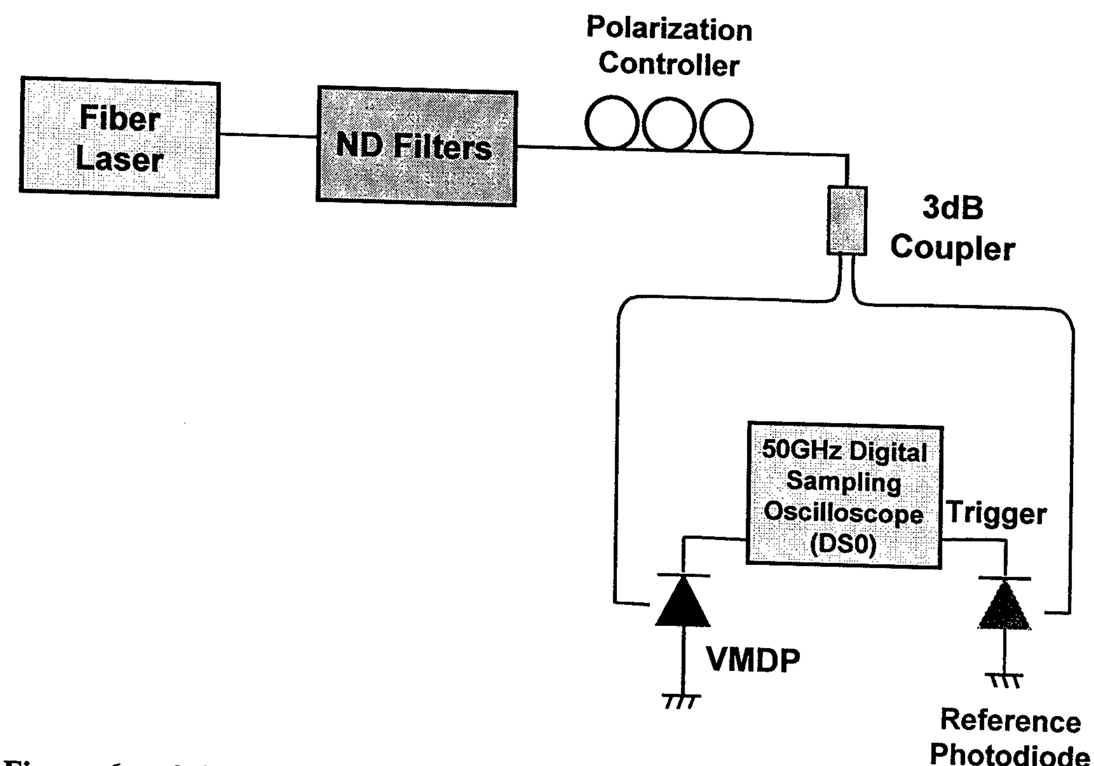

Figure 6. Schematic of the pulse response measurement setup. The fiber laser emits 160fs pulses at 40MHz repetition rate, wavelength at 1.55 um.

The pulse response of the VMDP under various bias and illumination conditions are shown in Figures 7a and 7b. There are two definite trends observed:

- Pulse gets broaden as optical power increases, probably due to saturation
- Device is bias dependent. At higher bias, pulse width is smaller and the long tail is better suppressed.

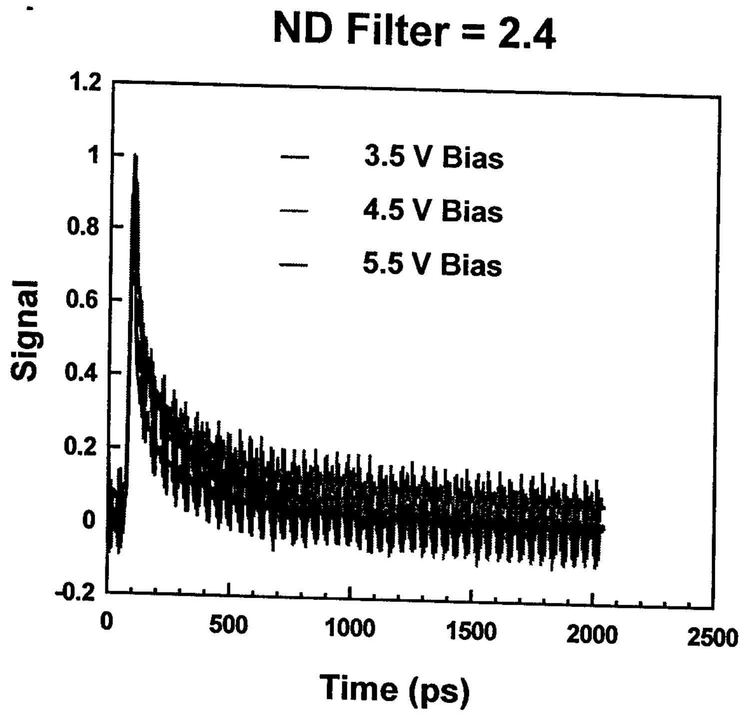

Figure 7a. Pulse response of VMDP (include cable, bias T, and probe) at different bias voltages, with ND filter = 2.4

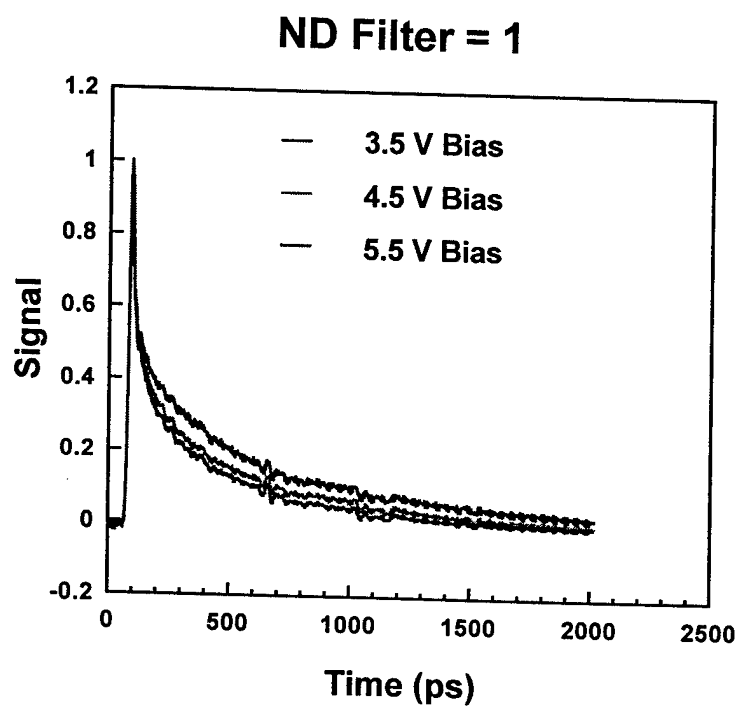

Figure 7b. Pulse response of VMDP (include cable, bias T, and probe) at different bias voltages, with ND filter = 1.0

The VMDP pulse response has a fast component, as seen in the narrow pulse width; but it also has a slow component which results in a very long tail. There are several possible reasons for the long tail:

1. Carriers trapping at the graded superlattice and Schottky barrier enhancement layers. Figure 2 shows a schematic cross section of the VMDP epitaxial layer structure. The band diagram is shown in Figure 3. If there is trapping at the barrier, it is more likely to be hole trapping since electron can easily overcome the barrier at high bias.

2. Slow diffusion of photo-excited carriers generated outside the high electric field region where the MSM fingers overlap. Figure 8 shows a schematic of the top view of one section of VMDP. The large mesa was used to avoid running the fingers over steep mesa edges, since for ebeam writing process, the metal fingers are in the order of a few hundred Angstroms thick only and could break easily.

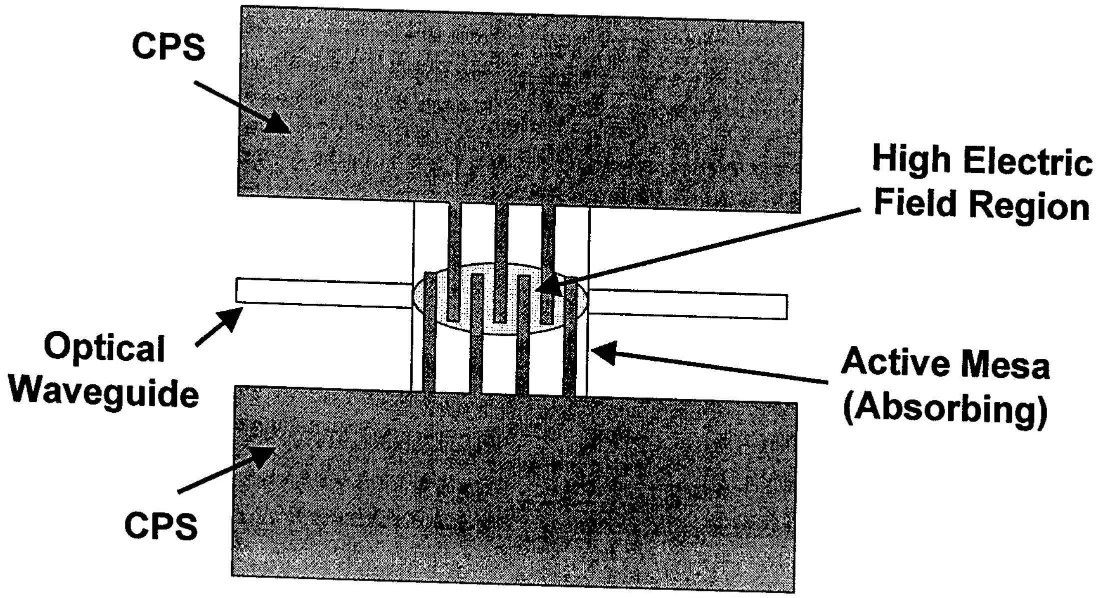

Figure 8. Schematic of a section of VMDP from top view. The high field region is where the fingers overlap

In order to investigate the long tail in the pulse response and isolate the two reasons listed above, we need to fabricate single MSM photodiode with submicron finger width and spacing on planar wafer (no mesa), with larger finger overlapping region for surface illuminated test. Since the finger overlap region is large, we can make sure not to illuminate outside this region so that all carriers generated should be under high field. We planned to fabricate the single device on three different wafers from TRW, Lucent, and EPI. The EPI wafer was grown by MOCVD and the buffer layer from active InGaAs layer to the InAlAs Schottky barrier layer is linearly graded, which should reduce the carrier trapping effect. We can also partially remove the InAlAs Schottky barrier enhancement layer by wet etching to reduce carrier trapping.

D3.4 Single MSM Photodetector

The single MSM photodiode was fabricated using Leica EBL100 electron beam writing machine at UCLA. Figure 9 shows a SEM picture of a single device. Different beam current and dosage were used for the fingers and contact metal pads. After exposure, the wafers were developed in 1MIBK:3IPA for 45 seconds. Surface cleaning in oxygen plasma and a short dip in hydrofluoric acid were employed before metal liftoff to reduce dark current. Finally, the fingers and pads were defined using standard liftoff, with metal thickness of 100Å Ti/ 600Å Au.

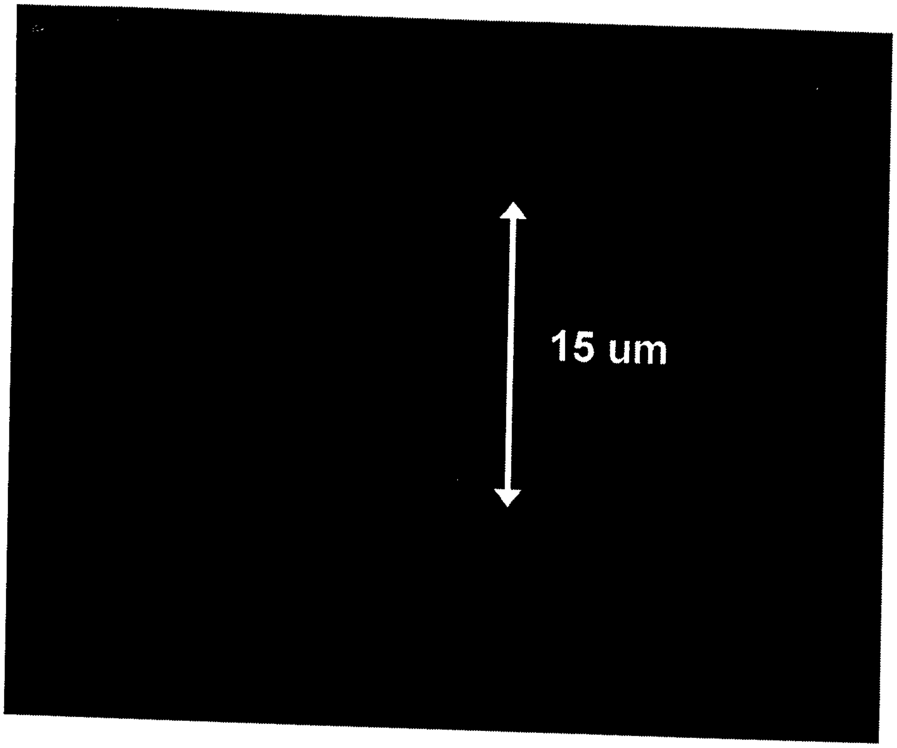

Figure 9. A Scanning Electron Micrograph (SEM) of a single MSMPD, with 600nm finger pitch and 15um finger overlap

The pulse response of the single MSMPD was characterized by an ultrashort laser pulse as for the VMDP. The device under test has an active area of 20um long, with 25um finger overlap. The contact pad is 30um wide and 40um long. The finger pitch (include finger width and spacing between fingers) is 600nm. The fiber laser output 160fs pulses at 40MHz repetition rate at 1.55um wavelength. A set of neutral density filters was used to vary the optical power input to the MSMPD. A 3dB coupler splits the signal into two paths: one is coupled to the MSMPD through a dispersion shifted lens fiber, and another is fed to a reference photodiode to trigger the 50GHz digital sampling oscilloscope. We carefully align the lens fiber from the top to illuminate only inside the finger overlapping region. The pulse response of a single MSMPD (TRW wafer) under various bias and optical power is shown in Figure 10a and 10b. The response include that of device, bias-T, cable and probe. The pulse width is about the same as of a 45GHz commercial detector that is connected with the bias-T and cable. Compare to the large mesa VMDP, the single MSMPD pulse response is shorter and has no long tail. The pulse width is within the limit of the measurement instruments.

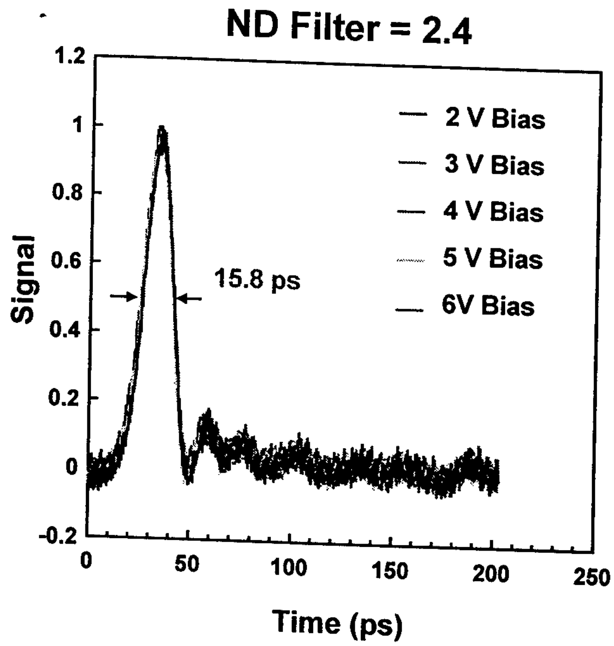

Figure 10a. Pulse response of a single MSMPD (include cable, bias T, and probe) at different bias voltages, with ND filter = 2.4

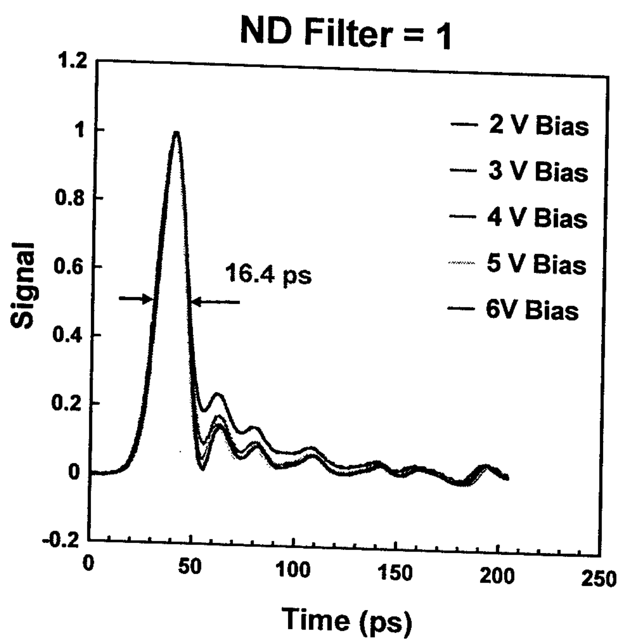

Figure 10b. Pulse response of a single MSMPD (include cable, bias T, and probe) at different bias voltages, with ND filter = 1.0

In conclusion, we have successfully fabricated and tested the single MSMPD, and confirmed that the long tail seen in our previous large mesa VMDP is not due to carriers trapping, but due to the slow diffusion of carriers generated outside the high field region where the MSM fingers overlap.

E. Conclusion and Future Direction

We have successfully fabricated and tested 3 generations of VMDP. Controlled experiments with split-contact CPS structure indicate most current generated by the first photodiode. This can be eliminated by etch down the passive waveguide through the core layer, and matching the width of the mesa and passive optical waveguide. A long tail also seen in impulse response of submicron finger VMDP, which has been identified as carrier diffusion in the large mesa. This can be avoided by placing the entire mesa under high field region, where MSM fingers overlap. A new design with these changes can help realize a truly high power, high speed VMDP.

F. Acknowledgements

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