

The contrast ratio was measured with the laser held at 835 nm and polarized 45° with respect to the stress axis. The wavelength was chosen such that a maximum difference in the dynamic rotation angle of the modulator was achieved at a 5 V. At this wavelength a contrast ratio of ~18:1 was achieved without an analyzer. By placing an analyzer in the output beam, we capitalized on the polarization rotation in the MQW due to the induced strain and the device becomes a polarization modulator. In this configuration, the contrast ratio was enhanced by a factor of 4 to ~55:1. It should be emphasized that the polarization rotation was achieved with light incident normal to the surface and the contrast ratio results are obtained without the benefit of a Fabry-Perot cavity.

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VIB-7 Ultrafast Single Photon Avalanche Diodes without Slow Tails in the Pulse Response—A. Lacaïta, M. Ghioni, S. Cova, and F. Zappa, Politecnico di Milano, Dipartimento di Elettronica ed Informazione and CEQSE-CNR, Piazza L. da Vinci 32-20133, Milano Italy Tel. +39-2-23996149; Fax +39-2-2367064.

Single-photon avalanche diodes (SPAD's), working biased above the breakdown voltage are the solid state alternative to photomultiplier tubes in high sensitivity measurements [1]. Applications are found in high performance optical-time-domain-reflectometry, millimeter satellite ranging, picosecond-resolved luminescence and fluorescent decay studies. The time response of conventional SPAD's is plagued by a wavelength-dependent tail, arising from carriers photogenerated in the neutral regions beneath the photodiode junction, reaching the depletion layer by diffusion [2]. This is a serious drawback in applications where weak signals must be detected just after strong peaks (i.e., Rayleigh scattering after a Fresnel reflection in optical fibers). In principle, reconvolution analysis could be employed to correct the data. In practice, this is seldom obtainable with good accuracy.

In order to completely suppress the diffusion tail, the neutral region beneath the photodiode junction should be eliminated, while maintaining a conductive path for the avalanche current. Our approach was to design a photodiode in a p epilayer grown on an n substrate. The proposed structure has a cylindrical symmetry. The photodiode junction was obtained with a shallow n⁺ phosphorus deposition. The sensitive area of the detector is defined by a boron p implantation which lowers the junction breakdown voltage to 21 V. The metal plate of the n⁺ contact acts as optical diaphragm which avoids photon absorption in regions outside the sensitive volume. When the avalanche is triggered, the current flows to a side ohmic contact on the p epilayer through a boron-implanted buried layer, interrupted just beneath the sensitive

area. At the operating conditions both the photodiode junction and the substrate-epilayer junction are reverse biased and their depleted regions get in contact in correspondence to the buried layer interruption.

This structure definitely avoids slow diffusion effects in the photodiode response, since only carrier photogenerated in the fully depleted volume and in the 0.3 μm thick upper n⁺ layer contribute to the photodiode signal. It is worth noting that due to the above-breakdown operation, the detector series resistance of a few kΩ does not impair the photodiode equivalent bandwidth. The measurements performed with a 20 ps laser pulse at 830 nm show a 50 ps pulse width of the detector response, completely free from diffusion tails over more than three orders of magnitude. Therefore the new device is able to detect -30 dB signals only 300 ps after the main peak. The comparison with the performance of more recent epitaxial SPAD's are striking. In these latter devices the neutral region beneath the photodiode junction was only 1 μm thick. Even this narrow neutral region causes a diffusion tail with an intensity only an order of magnitude less than the peak of the detector response and a lifetime of about 260 ps. Weak features of the light pulse are completely obscured by the residual tail for about 2 ns after the peak, while they can be clearly detected with the new device.

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VIB-8 110 GHz Si MSM Photodetectors—M. Y. Liu, S. Y. Chou, S. Alexandrou,* C. C. Wang,* and T. Y. Hsiang,* Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455 Tel. (612) 626-7174.

Previously, it was reported that metal-semiconductor-metal photodetectors (MSMPD's) had achieved 0.87 ps response time and 510 GHz bandwidth on low-temperature GaAs [1], and 10.7 ps and 41 GHz on bulk Si [2]. In this paper, we report a Si MSMPD with 3.7 ps response time and 110 GHz bandwidth. We also present the experimental and theoretical study of the factors that are important to the speed of Si MSMPD's, such as the photon absorption length, carrier diffusion length, carrier mean free path, finger spacing and finger width. Finally, we discuss new possibilities for even faster (~400 GHz) Si-based high-speed MSMPD's.

MSMPD's were fabricated on p-type Si wafers (10¹⁷ cm⁻³). Nanometer scale interdigitated metal fingers were defined using electron beam lithography and a lift-off. Coplanar transmission line contacts were made to the detectors for high-speed measurements. An electrooptic sampling system consisting of a wavelength tunable femtosecond Ti:Al₂O₃ laser and a LiTaO₃ sampling crystal was used to measure the impulse response of the detectors [3].

MSMPD's with 200 nm and 300 nm finger spacing and width were tested. When the laser wavelength was 725 nm, both detectors had a full width at half-maximum (FWHM) response time of 11 ps, independent of the finger structure. This is because the light absorption depth in Si at the wavelength is $\sim 5 \mu\text{m}$ and a large amount of carriers are generated deep inside semiconductor bulk, hence the diffusion time of the carriers from the bulk to the metal electrodes determines the device response time. However, when the laser wavelength reduced to 400 nm and the light absorption depth because $\sim 0.1 \mu\text{m}$, the detectors of 300 nm and 200 nm finger spacing and width showed, respectively, a response time of 5.5 ps and a bandwidth of 75 GHz, and 3.7 ps and 110 GHz.

The response times measured using 400 nm light pulse agree with a one-dimensional Monte-Carlo study of Si/MSMPD's [4], indicating that the detectors are transit-time limit. Furthermore, the Monte-Carlo study showed that with a proper scaling Si MSMPD's with 25 nm finger spacing and width can achieve 1 ps response time and 440 GHz bandwidth. We will discuss the scaling rules for high-speed operation and propose new MSMPD structures.

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VIB-9 Asymmetric Fabry-Perot Modulators with Millimeter-Wave (37 GHz) Frequency Response—C. C. Barron, C. J. Mahon, B. J. Thibeault, G. Wang, J. R. Karin, L. A. Coldren, and J. E. Bowers, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 Tel. (805) 893-8465; Fax (805) 893-3262.

Asymmetric Fabry-Perot modulators (AFPMP's) could serve as the optoelectronic link in high-speed smart-pixel interconnection and switching systems. They are interesting principally because their surface-normal configuration makes large arrays possible and their low voltage swings facilitate integration with electronics. We have designed and fabricated AFPMPs with good dc operating characteristics (20 dB contrast, 1.5 dB insertion loss) which also are capable of operating in the mm-wave regime. Previously we had demonstrated large-signal modulation of these devices at 20 GHz and predicted $f_{3\text{dB}}$ approaching 40 GHz. Here we present measurements attesting that these AFPMP's do indeed roll off at 37 GHz, a speed far higher than that of any other transverse modulators to date

[1], [2], and competitive with even the fastest traveling-wave modulators [3]–[6]. These high-speed AFPMP's should open possibilities of smart interconnection and switching systems with extremely high aggregate bit rates.

MOTIVATION

Since their introduction in 1989 [7], [8], asymmetric Fabry-Perot modulators (AFPMP's) have attracted a great deal of attention because of their high efficiency (high contrast, low insertion loss, and low voltage) and the fact that their surface-normal configuration is particularly compatible with fiber optics and with proposed architectures for optical free-space interconnection and switching systems. In addition to their other virtues, AFPMPs also have the potential for extremely high-speed operation, making them suitable for high-speed photonic switching applications in which the optical switches are "smart"—that is, they perform functions on the data stream at the data rate, rather than simply switching packets at some slower rate.

Last year we demonstrated small-signal modulation of AFPMPs to 21 GHz [9], from which we concluded that the modulation speed of AFPMP's seem to be RC-limited (at optical intensities well below the exciton saturation point). We surmise that, because the speed of the quantum-confined Stark effect relies on the rate at which the field switches, and not on the collection rate of the carriers, quantum-well modulators in general will not be limited by transit time at low optical powers. (At higher optical intensities, the bandwidth is transit-limited because of space-charge effects in the MQW material.) To test whether our hypothesis still holds for large-signal modulation, we designed a layer structure with a wide intrinsic region which minimizes the device capacitance while maintaining high-contrast, low-voltage-swing operation [10]. Then we fabricated $16 \times 20 \mu\text{m}$ diodes with low resistance ($\approx 100 \Omega$) and capacitance ($\approx 25 \text{ fF}$). At dc, these devices give 20 dB contrast and 1.5 dB (3 dB) insertion loss for a 6 V (4 V) swing about a $\approx 12 \text{ V}$ dc bias at $\lambda = 864 \text{ nm}$. We then proceeded to demonstrate large-signal modulation of these devices at 20 GHz with a swept-frequency experiment involving a CW Ti:Al₂O₃ laser and a high-speed photoreceiver [10].

OPTICAL CHARACTERIZATION TO 40 GHz

In the present experiment we use a mode-locked dye laser to produce a comb of frequencies separated by the repetition rate of the laser (80 MHz) and illuminate the modulator with this pulse stream. We then drive the device with a large mm-wave signal (up to $\approx 10 \text{ dBm}$, corresponding to $\pm 2 \text{ V}$ at the device) at a selection of frequencies between dc and 40 GHz, each separated by 10 kHz from one of the laser-generated comb frequencies. The resulting IF signal is detected by a low-noise, high-gain detector and fed to a spectrum analyzer. The calibrated response shows the expected 3 dB bandwidth of 37 GHz for equivalent cw incident optical powers less than