THERMAL RUNAWAY ANALYSIS FOR VELOCITY-MATCHED DISTRIBUTED PHOTODETECTORS

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ABSTRACT

The thermal runaway process for long wavelength velocity-matched distributed photodetectors (VMDP) with metal-semiconductor-metal photodiodes has been studied. We developed a numerical, three-dimensional electro-thermal model taking into account the nonlinearity of the substrate thermal properties and the nonuniform temperature rise due to self-heating. The analysis shows that the distributed nature of the photodetector allows it to work at high power level before catastrophic failure occurs. Examples are discussed to highlight the thermal behaviour of the distributed detector and to compare the model with experimental data.

INTRODUCTION

High power, high-speed photodetectors are key components in microwave fiber optic links to reduce RF insertion loss, and increase spurious free dynamic range and signal-to-signal ratio [1]. Previously we reported a GaAS/AlGaAs velocity-matched distributed photodetector (VMDP) operating at 860 nm; a peak saturaton photocurrent of 56 mA and a bandwidth of 49 GHz have been achieved [2]. For applications in RF photonic systems, however, InP-based longwavelength photodetectors, operating at 1.3 and 1.55 μm, are required. We recently reported [3] the first experimental results of InGaAs/InAlAs/InP longwavelength VMDP; since those are high-power detectors, thermal breakdown is a potentially serious problem, and a failure mechanism analysis is needed to improve the device performance and reliability. In order to investigate the thermal breakdown that leads to catastrophic damage in InP based photodetectors, a steady-state electro-thermal model is presented. Experimental results and some future design approaches are also discussed.

DESIGN AND FABRICATION

The schematic structure of VMDP is illustrated in Fig. 1. To increase the optical saturation power without compromising its bandwidth or efficiency, the MSM photodiodes are periodically distributed on top of a passive optical waveguide. The photocurrents are collected by a 50 ohm coplanar strips (CPS) microwave transmission line that is velocity matched to the optical waveguide. An advantage of VMDPs is the fact that the passive waveguide, the active photodiodes, and the microwave coplanar strips can be independently optimized. The optical waveguide is designed for low coupling loss and single mode operation. All photodiodes are kept below saturation by coupling a small portion of optical power from the waveguide. The microwave transmission line is designed to achieve velocity matching to the InP/InGaAlAs-based optical guide and 50 Ω characteristic impedance. Although the quantum efficiency of each MSM is low because of the high-power design, the total quantum efficiency of VMDP increases with the increasing number of photodiodes and can be very high thanks to the velocity match and series connection.

Each active MSM photodiodes consists of an InGaAs absorption layer, InGaAs/InAlAs graded superlattice layers, InAlAs Schottky-barrier enhancement layer, and Ti/Au fingers with thickness of 200 Å/2000 Å. Figure 2 shows the cross section of VMDP after mesa etching and an enlarged image of graded superlattice which 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. Our first experimental 1.2 mm long device, consisting of twelve MSM photodiodes, exhibited a 3 dB-bandwidth of 18 GHz and an overall quantum efficiency of 34% [3]. Actually, optical litography is employed to pattern MSM photodiodes, and the resulting finger width and spacing are both 1 μm. By scaling down to 0.1 μm, a frequency response in excess of 100 GHz is expected.

THEORETICAL MODEL

Typically, the reverse dark current of photodetectors increases with temperature. This additional current will in turn generate heat, which causes a further increase in temperature. At some point this process becomes unstable, resulting in uncontrolled current and temperature rise leading to catastrophic failure [4]. In order to evaluate this thermal runaway process, one must know the temperature dependence of dark current and the thermal distributions associated with the *IV* heating. The dark currents of the VMDP have been experimentally characterized for various bias voltages and temperatures. The temperature-dependent dark current is fitted to the theoretical model suggested in [5], as shown in Fig. 3. To find the temperature distribution of the device, a numerical, three-dimensional thermal model has been developed. Each MSM photodiode is modeled as rectangular source on top of the InP substrate. No heat flow through the sides, end facets or top surface of the substrate is considered. The heat generated by the MSM photodiodes is removed by a highly conductive sink, which is kept at room temperature T_0. With these boundary conditions, the temperature distribution can be obtained by solving the partial differential equation for steady-state heat conduction:

$$\nabla \cdot \kappa_T \nabla T = -Q \tag{1}$$

Assuming that the thermal conductivity is temperature indipendent, i.e. $\kappa_T = \kappa_0$ (with κ_0 thermal conductivity at T_0), the solution is obtained by expanding both the single source Q_s and the temperature T_s due to a single source into a double Fourier cosine series that matches the boundary conditions:

$$T_s(x,y,z) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \epsilon_m \epsilon_n \Psi_{mn} \cos\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) \tag{2}$$

$$Q_s(x,y,z) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \epsilon_m \epsilon_n \Phi_{mn} \cos\left(\frac{m\pi}{a}x\right) \cos\left(\frac{n\pi}{b}y\right) \tag{3}$$

The Green's function method as outlined in [6, 7] is used to find the coefficients of Fourier series. The solution to a multi-source problem is obtained by superimposition of the single-source solutions and non-linear thermal properties of InP substrate are included through a Kirchhoff transformation [8]. An iterative numerical scheme is used to obtain a self-consistent solution of the temperature distributions and the I-V characteristics.

RESULTS

Figures 4 and 5 show the calculated I-V characteristics for two different devices, denoted as VMDP1 and VMDP2. The first is a 400 μm long device with four $11 \times 48\,\mu\text{m}^2$ MSM photodiodes, while VMDP2 is a 600 μm long device with four $16 \times 48\mu\text{m}^2$ MSMs. Their theoretical quantum efficiencies are 17.2% and 24%, respectively. For an optical input power of 500 mW, VMDP2 has a breakdown voltage around 16 V and the corresponding damaging electrical power level is around 2.3 W. Reducing the size of MSM photodiodes, the generated thermal power decreases and the ensuing runaway process occurs at higher voltage.

The temperature distributions at the top surface of VMDP2, under 500 mW optical power and 17 V bias voltage, are shown in Fig. 6. At this operating point the thermal runaway process has already taken place and the temperature distributions show a dramatic difference between the first MSM (where a higly localized hot spot is formed) and the others.

Through figure 7 we can compare the theoretical I-V characteristics of VMDP2 and of a lumped MSM photodetector with the same active area. The same quantum efficiency (at low frequency) can be achieved in both structures; however, the distributed nature of VMDP results in an improvement of the breakdown voltage level.

Even if the operating optical power and bias voltage are kept well below the theoretical failure point the peak temperature in the device could still reach high values, accelerating the semiconductor device degradation. By intentionally stressing (high power, high bias) a few VMDP devices, we measured electrical power level at breakdown of 50 mW. For all devices tested to failure, visual inspection shows that the first photodiode is most severely damaged. The scanning electron micrograph (SEM) of a failed device is shown in Fig. 8, in which the degradation of the MSM fingers is clearly visible. More accurate inspection of failed devices by Energy Dispersive X-ray Analysis (EDX) shows gold diffusion into semiconductor material that, reacting with III-V compound, forms alloys of group- III elements and metal, which result into generation of defects and increased leakage current. The actual limitation due to gold diffusion could be overcome using Pt/Ti/Pt/Au as the

Schottky metal instead of Ti/Au. Pt has been proven to be better for diffusion barrier gold, besides having a larger Schottky barrier height.

CONCLUSION

We have demonstrated that the velocity-matched distributed photodetectors (VMDP) could work under high electrical power level before catastrophic failure occurs. In addition to high saturation current at high frequency, the distributed structure in VMDP can also increase the breakdown power level and total quantum efficiency by increasing the number of thermally isolated MSM photodiodes. Diffusion of gold into the semiconductor is shown to be a major reason for the small damaging threshold in the experimental devices.

ACKNOWLEDGEMENTS

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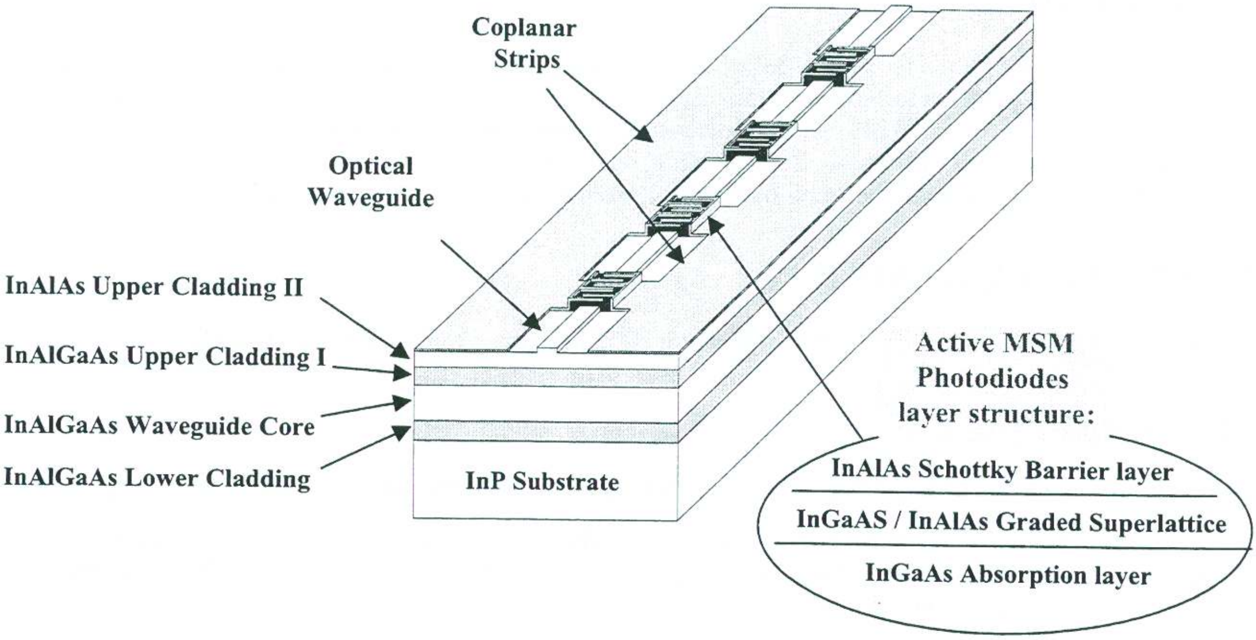

Figure 1: Schematic structure of velocity-matched distributed photodetectors (VMDP).

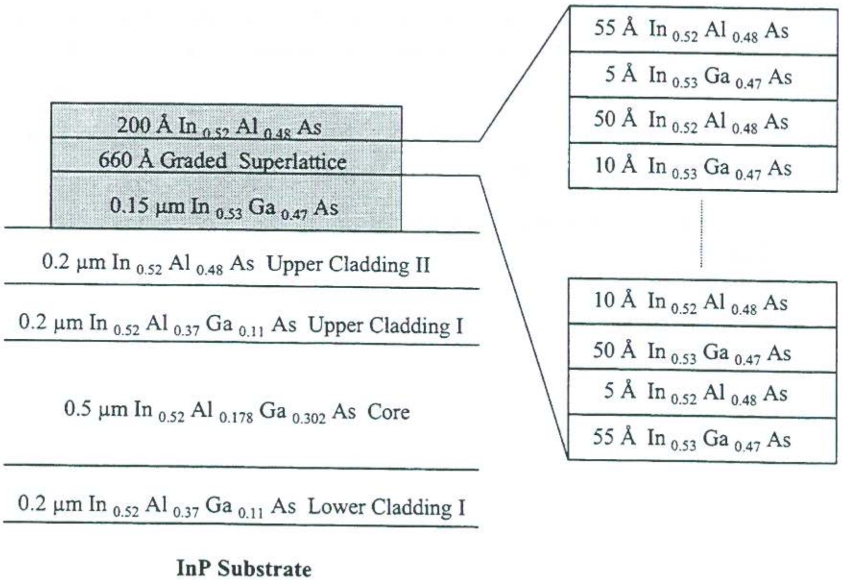

Figure 2: Schematic cross section of VMDP after mesa etching.

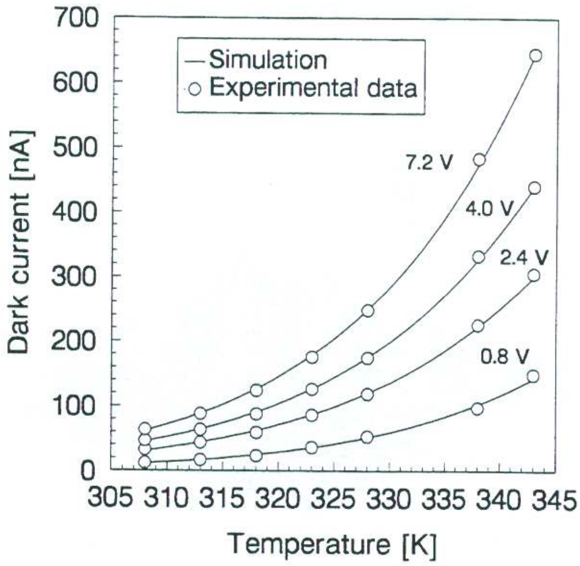

Figure 3: Dark current versus temperature for a 1.2 mm long VMDP device with eight $16 \times 48\,\mu m^2$ MSM photodiodes. The solid lines are the fit to the experimental points measured at different voltages.

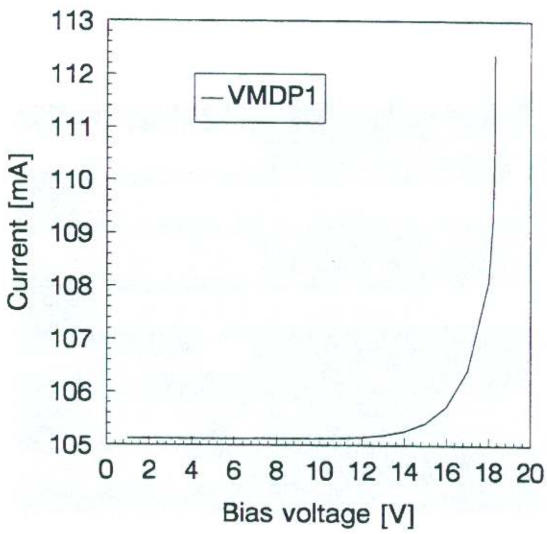

Figure 4: Theoretical I-V characteristics of VMDP1 consisting of four $11 \times 48\,\mu m^2$ MSMs. Optical input power is 500 mW. Both photocurrent and thermally dependent dark current have been considered.

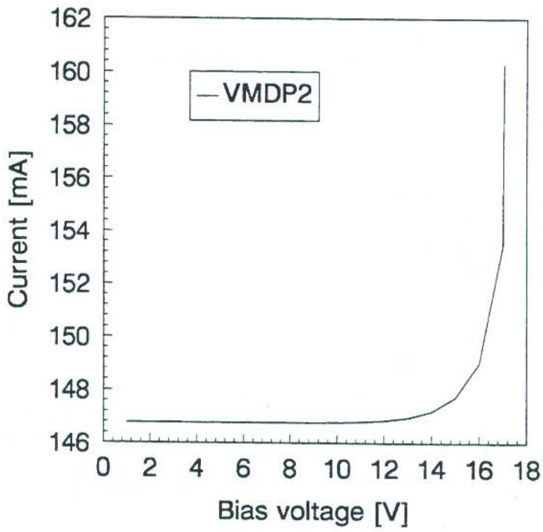

Figure 5: Theoretical I-V characteristics of VMDP2 consisting of four $16 \times 48\,\mu m^2$ MSMs. Optical input power is 500 mW. Both photocurrent and thermally dependent dark current have been considered.

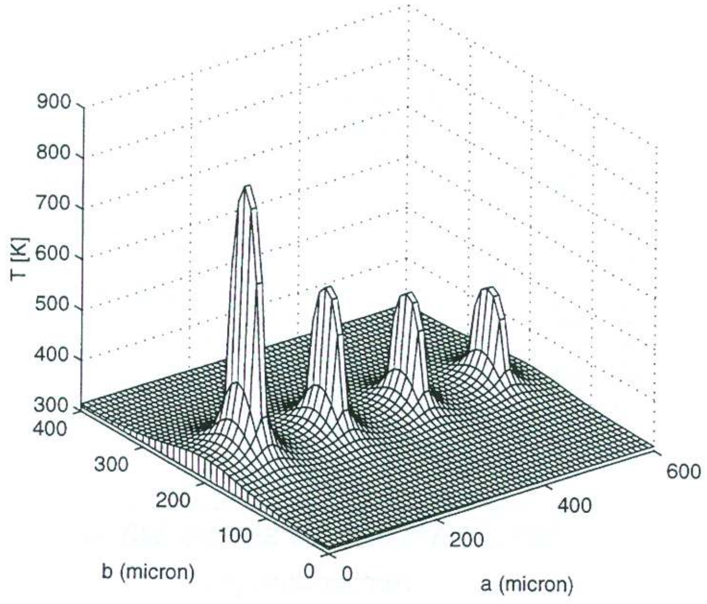

Figure 6: Temperature distributions on the surface of substrate for 600 μm long (axis a) and 400 μm wide (axis b) device with four MSM photodiodes ($16 \times 48\,\mu\text{m}^2$). Optical power is 500 mW while bias voltage is 17 V.

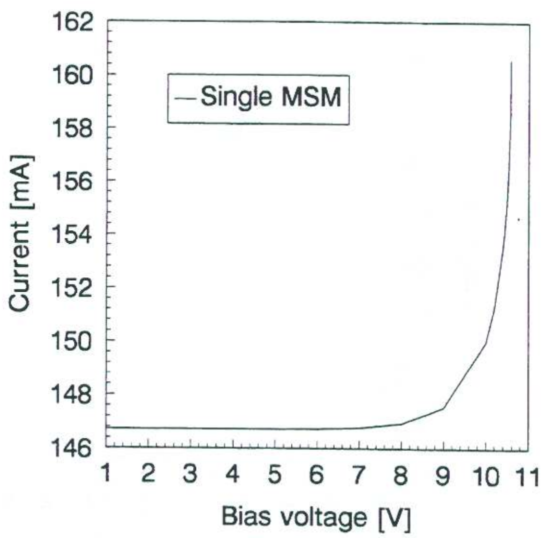

Figure 7: Theoretical I-V characteristic for single MSM with same total active area and total quantum efficiency (at low frequency) of VMDP2 consisting of four $16 \times 48\,\mu\text{m}^2$ MSMs. Optical input power is 500 mW, the current includes the photocurrent and a thermally dependent dark current.

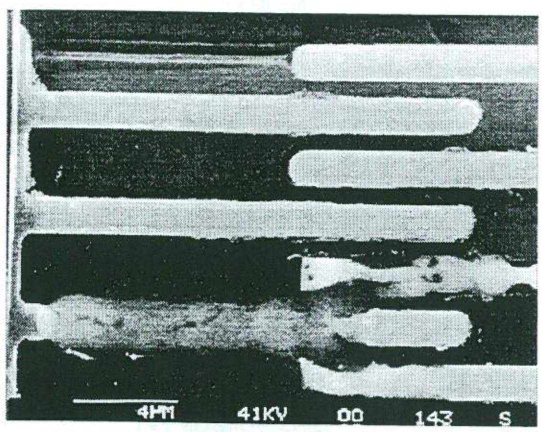

Figure 8: SEM picture of the first photodiode of a failed VMDP.