Photodetectors for microwave applications: a review and trends

Didier Decoster, Jean-Pierre Vilcot, Joe Harari, Vincent Magnin

Institut d'Electronique et de Microélectronique du Nord (IEMN), UMR CNRS 8520,
59652 Villeneuve d'Ascq, France.

ABSTRACT

After a review of conventional microwave photodetectors, this paper is dealing with the difficulties to fulfill applications requirements (responsivity, bandwidth, power), when the bandwidth is extended up to the millimeter wave frequency range. Up to date solutions are given and the validity of a new concept, the PIN photodiodes evanescently coupled to a multimode waveguide, is demonstrated.

Keywords: photodetectors, photodiodes, microwave, millimeter wave, multimode, diluted waveguide, evanescent coupling, uni-traveling carrier, traveling-wave, PIN, MSM.

1. INTRODUCTION

With the increasing performance of optoelectronic components, it becomes possible to envisage the marriage of microwave and optoelectronics which can lead to improved systems, characterized with new functionalities. A well known example is the use of optoelectronic components for analog links. It comes out, from research focused on this topic, that there are several main advantages to using optical components: integration improvements, insensitivity to electromagnetic field, propagation losses lower than 0.3 dB/km, bandwidth up to several 100 GHz.km, remote control function. An example of improvements using optics is optical phased array antenna control. The emerging direction of array antenna beam depends on delays or phases laws. It is defined by the path differences between the physical plane of the radiating components and the virtual plane perpendicular to the beam direction. Delays, instead of phase shifts, are needed to insure frequency independent beam steering. Optoelectronics is one of the most promising techniques that allows antenna to fit both aerodynamic requirements and whole space survey. In a system studied by Thales Airborn System, signal delay is optically obtained by associating switching matrixes with fibers of different lengths. This goal imposes very high quality microwave optical links with a high dynamic of the microwave signal. This dynamic is given by difference in dB between the noise floor and the maximum available microwave power without distortion. As a consequence, high power with high bandwidth and high responsivity photodetectors are needed. Starting from conventional microwave photodetectors, we will present state of the art solutions to fulfill these requirements in the microwave and millimeter wave domains.

2. CONVENTIONAL MICROWAVE PHOTODETECTORS

If we except avalanche photodiodes, with too low bandwidth for microwave applications, conventional microwave photodetectors are top-illuminated devices: Metal-Semiconductor-Metal photodetectors (MSM), Heterojunction Phototransistors (HPT) and PIN photodiodes.

MSM are attractive devices for microwave application[1]. They are constituted of two Schottky contacts deposited on semiconductor material. Their structure is completely compatible with microwave monolithic integrated circuits. Because of their planar structure the capacitance is very low, and the frequency limitation is mainly due to transit time. They suffer from low responsivities due to shadow effects of the electrodes and from degradation of transit time because deep generated photocarriers follow long electrical field lines. Strong electrical field peaks occur near the electrodes, causing early breakdown which limits the microwave power available at the output of the device.

Several authors pointed out the potentialities of HPT for microwave applications[2,3]. An heterojunction phototransistor can be considered as an heterojunction bipolar transistor (HBT) for which the base-collector junction is used as a photodiode. Consequently, it combines the properties of the HBT and the photodiode monolithically in the same device. The first function of an HPT is, obviously, the photodetector with internal gain. The advantages compared to the classical avalanche photodiode are high bandwidth, low bias voltage and low noise. The second function is a transistor optically controlled. The photocurrent acts as a base current, and the total base current of the transistor is then optically tuned. This aspect can lead to various applications, such as the optical control of microwave oscillators. The last function of these devices is the optoelectronic mixer. Two electrical signals can be mixed onto the device through one or two optical carriers; with one optical carrier, the second signal is applied on the transistor. As for the MSM photodiode, the structure of the phototransistor is completely compatible with the technology of the (HBT) microelectronics. But the weakness of this device seems to be the power limitation, in spite of recent efforts to overcome this difficulty[4].

Top-illuminated PIN photodiodes remain the most popular devices and a lot of works demonstrated their high responsivity for bandwidth up to 20 GHz. The maximum output power is significantly higher than for MSM and HPT, but varies as the inverse of the detector volume[5], thus is reduced when the bandwidth increases. This point will be discussed more precisely later.

3. MILLIMETER WAVE PHOTODETECTORS

It is well known that edge-illuminated photodetectors (MSM, HPT, and PIN) are suitable devices to increase the bandwidth with keeping high responsivity[6]. Focusing on PIN photodiodes, high speed requires short transit time and small capacitance. As a consequence, for very high speed (millimeter wave) applications, the absorbing region of photodiodes must be thin, typically 0.4 µm and less for cut off frequency higher than 60 GHz. With vertical illumination so thin absorbing layer leads to small quantum efficiency. The well known solution to overcome this trade off is the lateral illumination. The photodetector is similar to an optical waveguide with an absorbing core, and is called PIN waveguide photodetector. To get a good coupling to the optical fiber, a multimode structure is more suitable. A typical epitaxy on InP semi-insulating substrate is then: a nid GaInAs absorbing layer between two (n and p types) GaInAsP and InP confinement layers, with a GaInAs p-type contact top layer. As an example, devices fabricated at IEMN exhibit a 4 µm etched rib waveguide, an input facet obtained by cleaving, with a total device length ranging around 10 to 20µm. With a lens-ended fiber, quantum efficiency higher than 60% without anti-reflection coating can be achieved with cut-off frequency over 60GHz. A semi-insulating substrate and a coplanar line improve the microwave access by reduction of parasitics (capacitance…) The semi-insulating substrate allows the monolithic integration of a passive reactive network with the PIN waveguide photodiode to reduce the large impedance mismatch between the PIN photodetector and the 50 Ω of the microwave world in a small bandwidth.

Power limitation (≅ 0 dBm at 60 GHz) occur in so small devices[4], due to high density of photocarriers killing the electric field in the intrinsic region and high photocurrent reducing the bias voltage in the external circuit. To solve this problem, two ways are possible : the traveling wave photodetector (TW) with a long length (and hence volume) with electrodes designed to get a 50 Ω microwave line, and the uni-traveling carrier (UTC) photodetector (figure 1) for which photodetection takes place in a thin p-type highly doped absorbing layer. TW photodetectors are very long PIN waveguide photodiodes included in a 50 Ω microwave line[7,8,9]. In principle, if optical and microwave signals propagate at the same velocity, no bandwidth limitation occurs. It is difficult to achieve velocity and impedance matching, and the microwave losses in the microwave line reduce the possible length around some hundred microns. The main consequence is that it is difficult to achieve a true TW photodiode. Up to now best results are obtained with velocity-matched distributed photodetectors for which several MSM, PIN or UTC photodetectors are placed along a 50 Ω microwave line[10,11].

UTC photodetectors are derived from HBT. They are $p^+n^-n^+$ structure for which the p^+ layer is the absorbing region. Only electrons contribute to the photocurrent and move towards the n^+ region thanks to diffusion in the p^+ absorbing layer, and drift in the n^- collector. Because the electrical field vanishes in the p^+ absorbing layer, the high illumination has, in principle, no effect on the responsivity and dynamic of the photodetector, which would be able to supply high microwave power. Recent experimental results[12] showed the potentialities of UTC for high power and high bandwidth. The price to pay is a low responsivity for top illuminated devices, since the p^+ absorbing layer must be thin for fast collection of electrons.

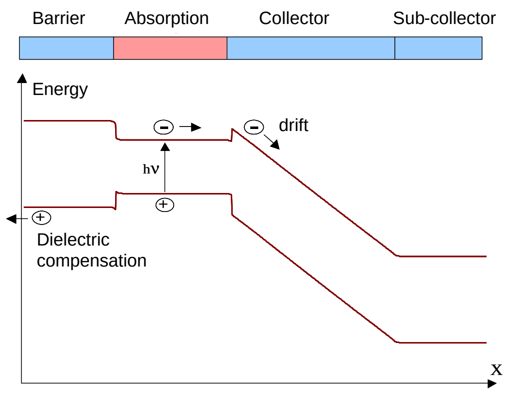

Figure 1: band structure of an UTC photodiode. Only electrons pass through the collector.

4. A NEW CONCEPT: DILUTED MULTIMODE WAVEGUIDE PHOTODIODES

The direct illumination scheme used in edge-illuminated photodetectors has some known impairments: input facet fabrication with junction passivation is difficult to achieve with high reliability[13]. To overcome these impairments, high speed edge illuminated, evanescently coupled PIN photodiode are attractive devices. This method allows fabrication of junction using conventional diffusion technological process, as for conventional top-illuminated devices, and avoid junction at the semiconductor surface. In a recent device[14], a taper was included in the input waveguide, leading to better alignment tolerance to the fiber. But the tapered waveguide exhibits excess loss which reduces the responsivity. It is the reason why another way based on a new concept is the use of a diluted multimode input waveguide, followed by the evanescently coupled PIN photodiode. The diluted waveguide is made of very thin GaInAsP quaternary epilayers introduced in InP. The distance between the quaternary epilayers decreases from the substrate to the top of the waveguide to get a specific waveguide which can be compared to a half lens whose centre is on the top of the waveguide (figure 2). Because of this lens, the coming on light is pushed towards the surface of the waveguide, and then reflected at the air-semiconductor interface, and so on leading to a "snake" propagation of the light (figure 3). This specific behavior is typical for a multimode propagation. The new idea is to apply this behavior to evanescently coupled PIN photodiodes. The light beam can be steered towards the photoabsorbing layer over very short coupling length, allowing high speed photodetection, very high responsivity, and high alignment tolerance. The difficulty is here to design the multimode waveguide. In principle, it is just necessary to place the absorbing region over the area where the beam is reflected, at the air-semiconductor interface. In practice, due to numerous technological parameters, the device is very difficult to optimize and, at IEMN, we use genetic algorithm coupled to a 2D-BPM.

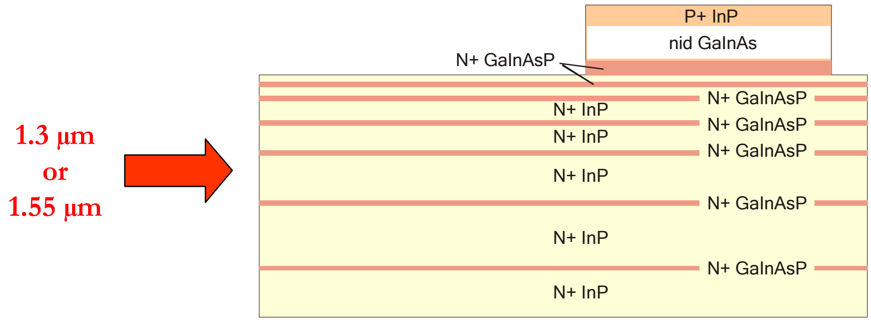

Figure 2: multimode evanescent coupled PIN waveguide.

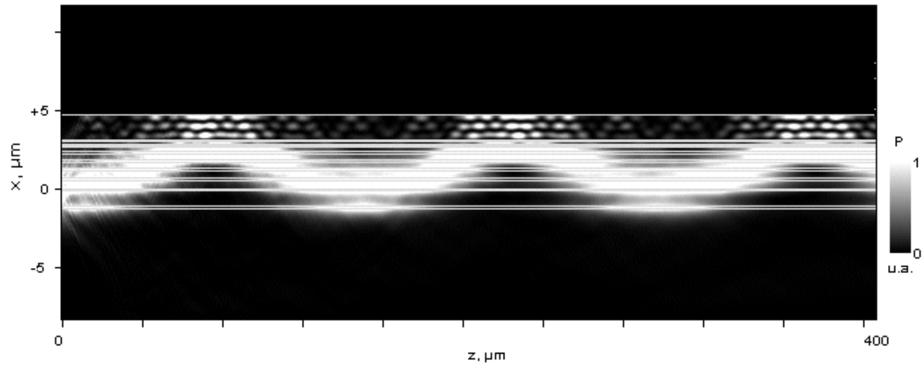

Figure 3: simulated propagation of light in a diluted multimode waveguide (2D-BPM) at 1.3 µm in TM mode. The vertical axis is dilated to allow a better perception of the "snake" behavior.

Genetic Algorithms (GA's) are based on Charles Darwin's theory of evolution[15]. GA's operate on a population of N devices, each being a potential solution to the problem. A device is represented by binary strings, called chromosomes, coding the variables of the problem. After initialization of these variables during genesis phase, a temporal loop makes the population evolve during two hundred generations (figure 4). At each step, devices are evaluated using a fitness function, which will guide the selection of the surviving part of the population. Couples of surviving mates are formed to generate offspring by crossover operation on their chromosomes and random mutations. As time goes on, the population mean fitness tends to ameliorate.

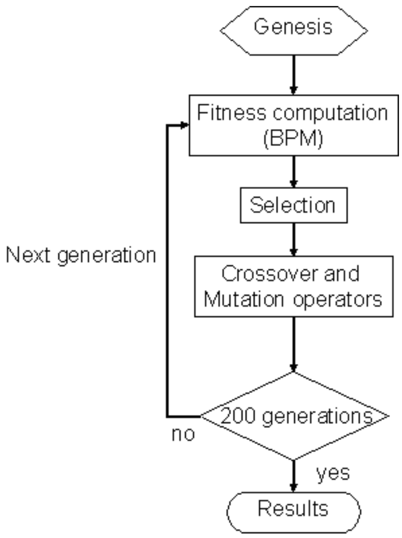

Figure 4: the genetic algorithm.

The physical model used to evaluate the fitness function of each photodiode is a classical 2-dimensional finite difference Beam Propagation Method (BPM) with scalar and paraxial approximations. The population size was fixed to 100 devices.

To test the validity of this new concept, side-illuminated p-i-n photodetectors were designed, optimized and fabricated. The targeted functionalities of these photodetectors are a very high responsivity at 1.3 µm and 1.55 µm wavelengths, quasi-independent to the optical polarization, and a high tolerance to fiber alignment. A first structure was optimized for coupling with a cleaved fiber having a 9.0-µm mode width (at 1/e) at 1.3-µm wavelength and 10.5 µm at 1.55 µm. The vertical position of the fiber axis was fixed to 5 µm below the waveguide surface in order to follow a scheme of hybrid surface integration. The photodiode maximum length was fixed to 200 µm leading to a minimum cut-off frequency around 2.5 GHz. The 1.05 µm wavelength quaternary ($Q_{1.05}$) lattice matched to InP has been chosen. The number of quaternary epilayers in the waveguide structure was fixed to 8. The length of the input waveguide was fixed to 50 µm. A second structure was designed for a lensed fiber whose mode diameters are 5.1 and 5.5 µm respectively at 1.3 and 1.55 µm. The fiber axis position was fixed 3 µm below the waveguide surface. The matching epilayers were made with the 1.18-µm wavelength quaternary lattice-matched to InP.

The optimized structures were fabricated and characterized at ALCATEL-OPTO+. The measured performances for the cleaved fiber structure, in excellent agreement with predicted results[16,17], are responsivities of 1.03 and 0.86 A/W respectively at 1.55 and 1.3-µm wavelengths, a corresponding vertical alignment tolerances of 6.7 and 6.4 µm at -1dB (11.0 and 10.7 µm at –3 dB) and almost no polarization dependence (maximum 0.1 dB). Concerning the lensed fiber structure, measured performances, also in excellent agreement with predicted results[16,17], are responsivities of 1.22 and 1.02 A/W respectively at 1.55 and 1.3-µm wavelengths, a corresponding vertical alignment tolerances of 5.9 and 5.4 µm at -1dB and almost no polarization dependence. The cut-off frequency is in excess of 3GHz and works are in progress to extend the bandwidth up to the millimeter wave frequency range. First theoretical results predict that bandwidth in excess of 40 GHz with high responsivity can be achieved with this technique by a reduction of the coupling length to 25 µm, if we accept a device working only at 1.55 µm wavelength, keeping a good tolerance to alignment with a lens-ended fiber.

5. CONCLUSION

Microwave optical links are basic bricks for new systems such as optically supplied antennas. For these applications, the dynamic of the link is one of the main parameter to be achieved. To increase this dynamic, high power microwave photodetectors are needed. For very high bandwidth, up to the millimeter wave domain, the photodetector must be edge-illuminated, to keep the responsivity high. But its volume lust be reduced, which is not compatible with the power. One possible solution experimentally demonstrated is the use of uni-traveling carriers (UTC) photodetectors for which the absorption occurs in a very thin p^+ layer. As a consequence top-illuminated UTC photodetectors suffer from low responsivities. We recently demonstrated, theoretically and experimentally, the validity of a new concept: PIN photodiodes evanescently coupled to a multimode waveguide. Very efficient photodetectors were fabricated, based on this concept. Works are in progress to demonstrate its validity for high responsivity millimeter wave photodetectors, and next step will be to combine this concept with UTC photodetectors, to get efficient high speed and high power photodetectors.

ACKNOWLEDGMENTS

This work is the result of a fruitful collaboration between IEMN and ALCATEL-OPTO+. We would like to thank Louis Giraudet, from ALCATEL-OPTO+, for the numerous discussions about the concept and the design of these photodiodes. The fabrication of the devices were entirely made by ALCATEL-OPTO+. We would like to thank Mohand Achouche from ALCATEL-OPTO+ for the collaboration on 40 GHz PIN and UTC photodiodes. Studies on UTC photodiodes were supported by the French Ministry of Research in the frame of the RNRT Popeye project. We would also like to thank Jean Chazelas from THALES AIRBORN SYSTEM for discussions about microwave photonic applications.

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