STEADY AND TRANSIENT SIMULATIONS OF PHOTODIODES

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Steady and transient simulations of Silicium and GaInAs/InP photodiodes for .85 and 1.55 um optical communications are performed.

Influences of the incident optical power over sensitivity, linearity and response time are performed.

It is shown that steady state analysis allows low CPU time cost and good prediction of the response time.

I- INTRODUCTION

Different optical communication applications call for different photodetection techniques (direct or heterodyne) and for different photodetectors according to the chosen wavelength.

For long distance optical communications a GaInAs/InP photodiode along with low dispersion fiber in the 1.55 um optical window can be chosen, using heterodyne detection which significantly improves signal to noise ratio.

For shorter distances and lower bit rates a cheaper solution consists of a .85 um emitter along with a PIN Si photodiode.

In direct detection the optical power received on the photodiode must not be smaller than 10^{-6} W, for operationnal optical communications.

On the opposite, in heterodyne detection the photodetector receives, along with the small optical signal, a large optical power, issued from the local oscillator (monomode laser). An optical output of a few mW (typical output of a semiconductor laser) falls on a 100 µm2 surface area(area of the core of a monomode fiber). Such an optical power corresponds to a flux of some 10^{22} photons/s/cm2.

Such conditions on the photodectors lead to different numerical simulation problems.

Electrochemical and electrostatic potentials are adequate to describe both the dark reverse current (direct detection) and the very high injection conditions (heterodyne detection) for which the predominant recombination - generation term usually leads to numerical instability, especially in the transient case (2)

II- SET OF EQUATIONS AND NUMERICAL SCHEME

Under the assumption of cold carriers the general set of equations that describes heterostructure is given by:

$$\mathrm{div}\ \varepsilon\ \mathrm{grad}\ \phi = q\ (n - p - C) \qquad (1)$$
$$\partial n/\partial t = 1/q\ \mathrm{div}\ Jn - U + G \qquad (2)$$
$$\partial p/\partial t = 1/q\ \mathrm{div}\ Jp - U + G \qquad (3)$$

For isothermal graded heterostructures the conduction current are given by :

$$Jn = n\,\mu_n\ \mathrm{grad}\ Efn \qquad Efn = -\,q\,\phi_n \qquad (4)$$
$$Jp = p\,\mu_p\ \mathrm{grad}\ Efp \qquad Efp = -\,q\,\phi_p \qquad (5)$$

where Efn and Efp are the electron and hole electrochemical potentials. Carriers densities can be described either in Maxwell-Boltzmann or in Fermi-Dirac statistics. In the latter case:

$$n = N_c \mathcal{F}_{1/2}(-q\Phi_n/kT) \qquad \text{with} \quad q\Phi_n = -q\phi - \chi + q\phi_n$$

$$p = N_v \mathcal{F}_{1/2}(-q\Phi_p/kT) \qquad \text{with} \quad q\Phi_p = -q\phi_p + q\phi + \chi + E_g$$

U is the thermal recombination-generation rate which must then be written in Fermi-Dirac statistics.(3). G is the external optical generation rate.

The equations are linearized and the set of equations is solved within an uncoupled scheme of resolution; Poisson equation as a function of the electrostatic potential and the continuity equations as a function of electron and hole electrochemical potentials respectively.

In electron and hole continuity equation, carrier densities and thermal recombination-generation rate are all linearised around an approximate solution :

$$n(\phi_n) = n(\phi_\circ,\phi_n) = n(\phi_{n\circ}) + \frac{dn}{d\phi_n}\Big|_{\phi_{n\circ}} \delta\phi_n$$

$$p(\phi_p) = p(\phi_\circ,\phi_p) = p(\phi_{p\circ}) - \frac{dp}{d\phi_p}\Big|_{\phi_{p\circ}} \delta\phi_p$$

$$U(\phi_n,\phi_p) = U(\phi_\circ,\phi_n,\phi_p) = U(\phi_{n\circ},\phi_{p\circ}) + \frac{\partial U}{\partial\phi_n}\Big|_{\phi_{n\circ}} \delta\phi_n - \frac{\partial U}{\partial\phi_p}\Big|_{\phi_{p\circ}} \delta\phi_p$$

High optical power leads to an important generation-recombination rate which must therefore be correctly linearized.

Transient response are described with variable time steps greater than the dielectric relaxation time (4) using a variable implicit method (the degree of implictness c varies from .5 to 1 throughout the transient), accordingly with the evolution of the device response (4).

This electrostatic and electrochemical potential representation, along with a correct description of thermal recombination-generation rate allows exellent description of reverse bias heterostructures in Fermi-Dirac statistics.

The transient numerical scheme used and previously described (5) precisely describes a transient with few time steps.

III- DESCRIPTION OF THE SIMULATED STRUCTURES

The simulated Si and GaInAs/InP PIN photodiodes are described in table I and II.

For .65 µm and .85 µm wavelength, the Si PIN diodes intrinsic layer are 10 um and 20 um wide with absorption coefficient of 3.10^3 cm-1 and 600 cm-1.

Bias of -10 V and -20 V give, for low optical power, an uniform electric field of some 10 kV/cm, for which the carriers are supposed to reach their optimal drift velocity

At the 1.55 µm wavelength the absorption coefficient of $Ga_{.47}In_{.53}As$ material is 7.10^3cm-1, whereas InP material is transparent. Thus front or back illumination can be used even with a 200 µm thick InP substrate. The P N junction is located in the absorbing region. A N^- layer (10^{16} cm-3) InP layer inhibits exodiffusion of phosphorous from then N^+ InP towards GaInAs.

The behaviour of the photodiodes are simulated for fluxes from 10^{17} to 10^{23} photons/s/cm2, corresponding to optical powers of 10^{-2} to 10^{4} W/cm2

IV- STEADY STATE RESULTS

The electric potential distribution, in the intrinsic layer, is not uniform for high optical power. The potential drop is located at the P^+N^- and the N^-N^+ junctions and leads to high electric fields in these areas, the carriers having already reached their optimal drift velocity.

Increasingly large area of low electric field spread in the intrinsic layer when increasing optical power.Fig 1

For high optical power in Si PIN photodiodes a non negligeable electric field appears in the bulk N^+ material, allowing carrier collection on a greater distance than the diffusion length. Hence the sensitivity slightly improves but less than 1%.

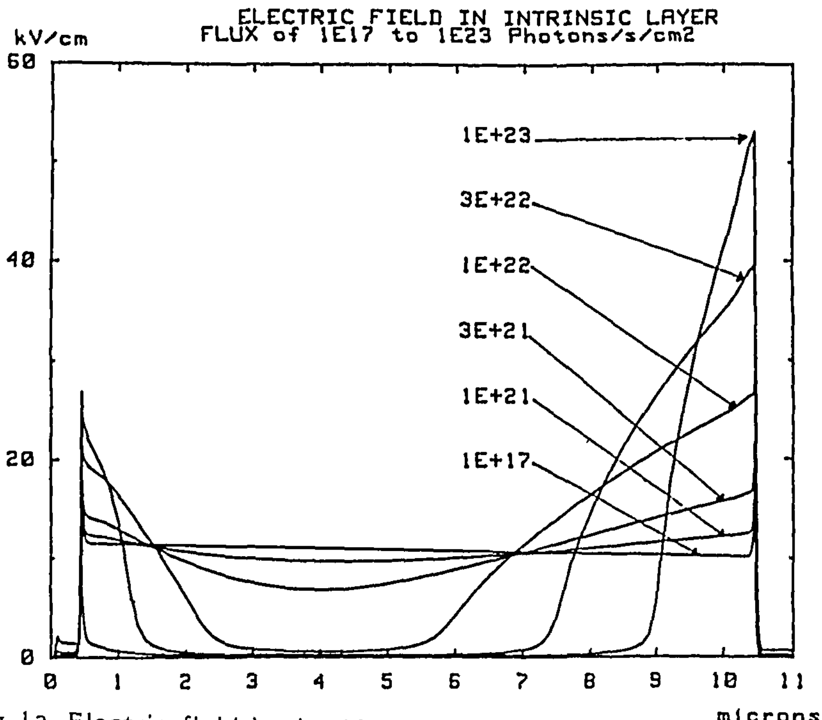

Fig 1a Electric field in the 10 um intrinsic layer Si diode

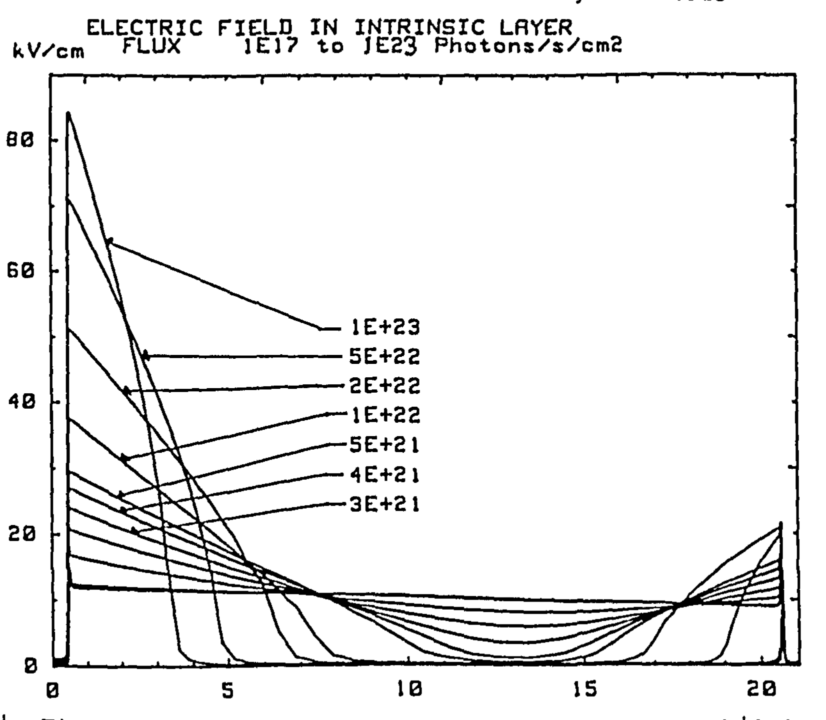

Fig 1b Electric field in then 20 um intrinsic layer Si diode

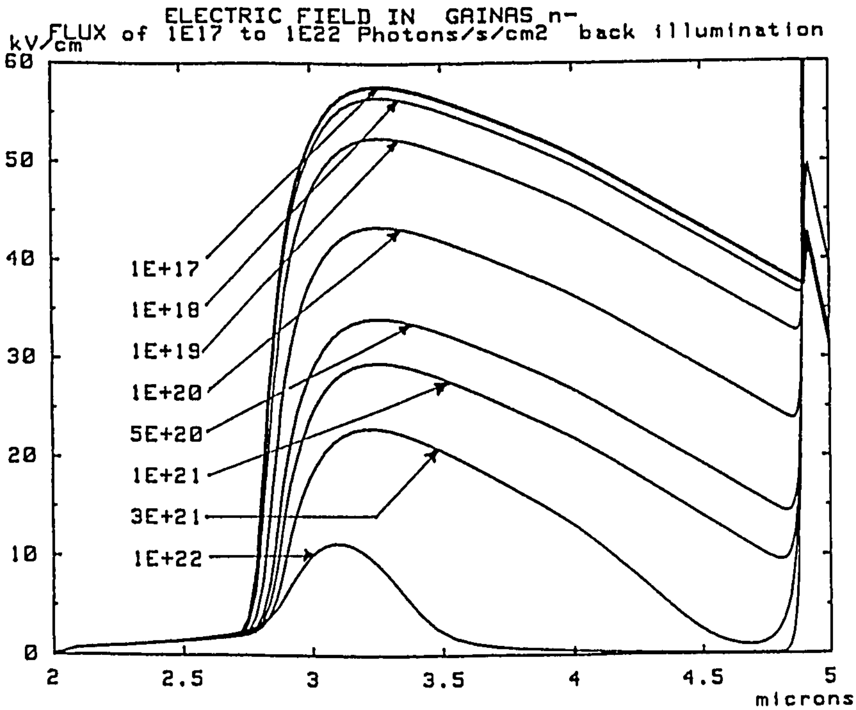

Fig 1c Electric field in the intrinsic layer of GaInAs/InP diode

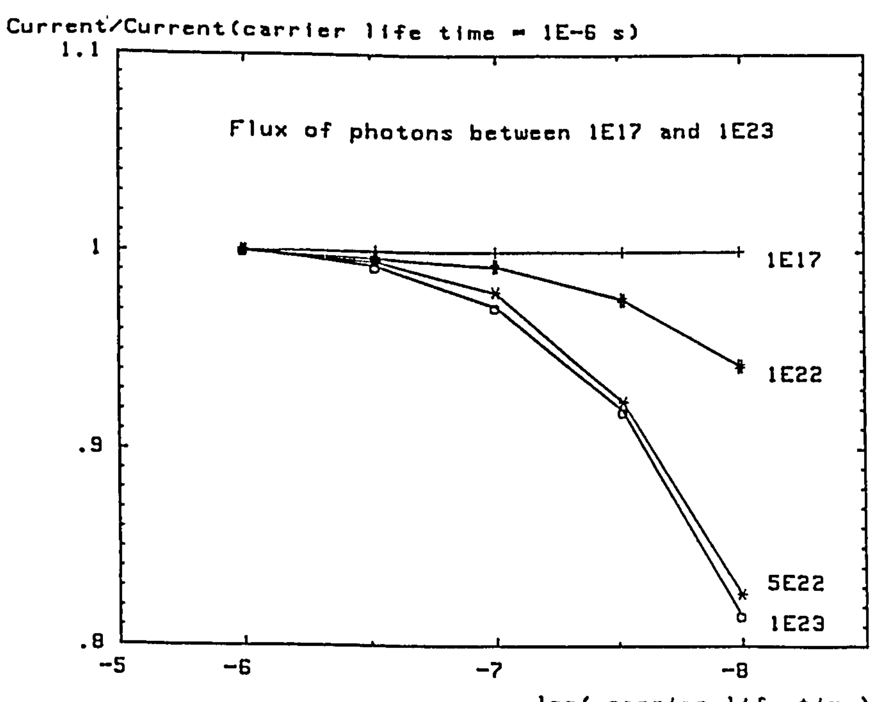

Fig 2

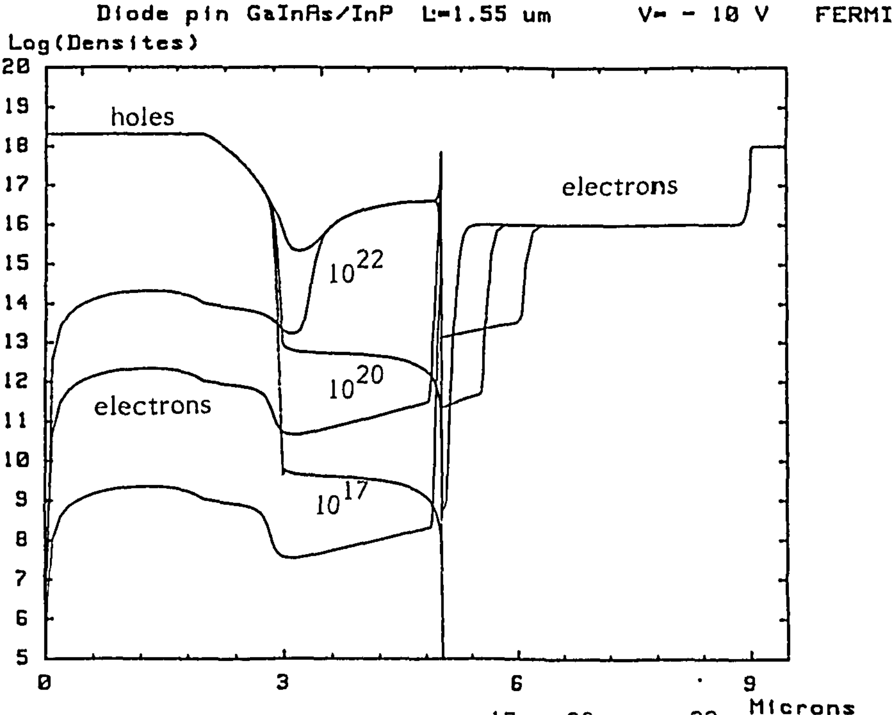

Fig 3 Carrier densities for flux of 10^{17}, 10^{20} and 10^{22} photons/s /cm2

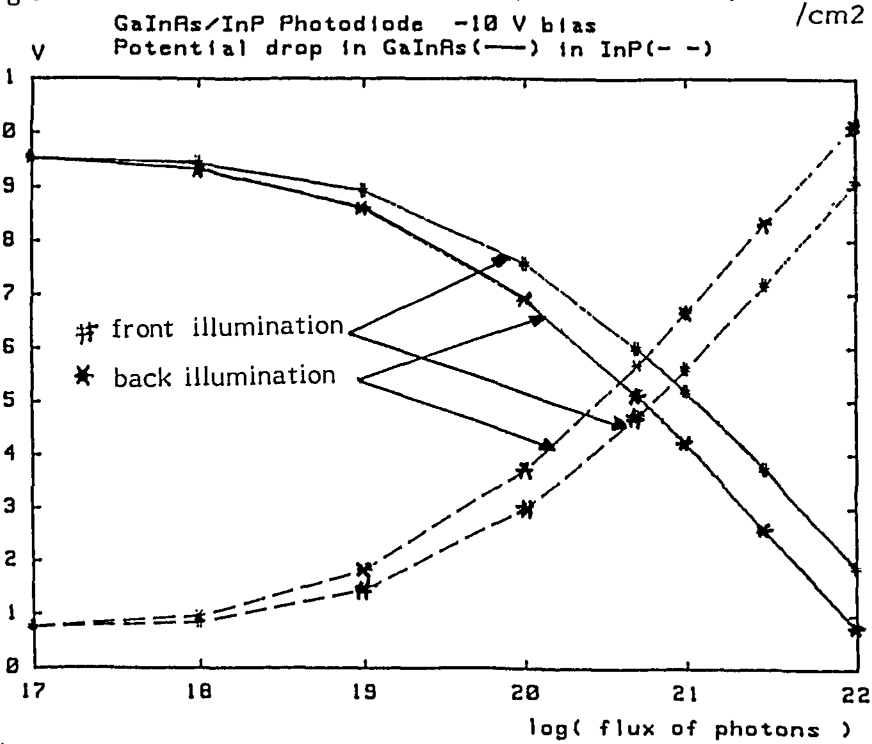

Fig 4

The evolution of the distribution of the electrostatic potential in the intrinsic layer for large optical powers has far greater consequences. Drift in the low electric field area can be unsufficient to collect carriers before they suffer recombination in too poor quality material. The transit time across the intrinsic layer is then no longer small compared to the carrier life time τ_n, τ_p. For good quality material (carrier life time 10^{-6} s) the photodetector has a linear response for photons fluxes ranging between 10^{17} and 10^{23} photons/s/cm2, whereas linearity falls for poorer quality materials.Fig 2

The same electric field behaviour is observed in the GaInAs/InP photodiode. For large optical powers a potential drop appears in the N^- InP layer, to the detriment of the voltage drop in the N^- InGaAs layer. As described in Table II, InP has a lower electron mobility than GaInAs (6)

Back illumination gives better sensitivity (.9 A/W) than front illumination (.45 A/W) since optical absorbtion directly occurs in the intrinsic region as it is shown by the carrier densities in GaInAs at the vicinity of the heterojunction.Fig 3. But back illumination gives a higher potential drop in the N- InP layer than front illumination does, as shown on Fig 4.

It can be expected from the steady state results that the time response of the photodiodes will be influence by the optical power.

V- TRANSIENT SIMULATION

Time response along with sensitivity and linearity is one of the major parameter of a photodetector.

Numerical simulation of the rise time of PIN photodiode is performed. The rise time to a step of optical power is given by the elapsed time between the 10% and the 90% current response to the signal (7). Rise time is related to the transit time whereas carrier diffusion also influences decay time.

The electron and hole current response of the GaInAs/InP photodiode to a step of power of 10^{16} to 10^{17} photons/s/cm2 is described on Fig 5. A constant number of 5 time steps per time decade was used. At each time step the total current (displacement current and conduction currents of electrons and holes) is computed across the whole structure as Fig 6 shows.

For high injection conditions, greater rise time must be described (due to the low electric field area). The important recombination-generation does not then allows so large time steps as those used for low optical power, and the overall convergence of the resolution scheme is also poorer(2). Transient response to large optical power thus requires large CPU time.

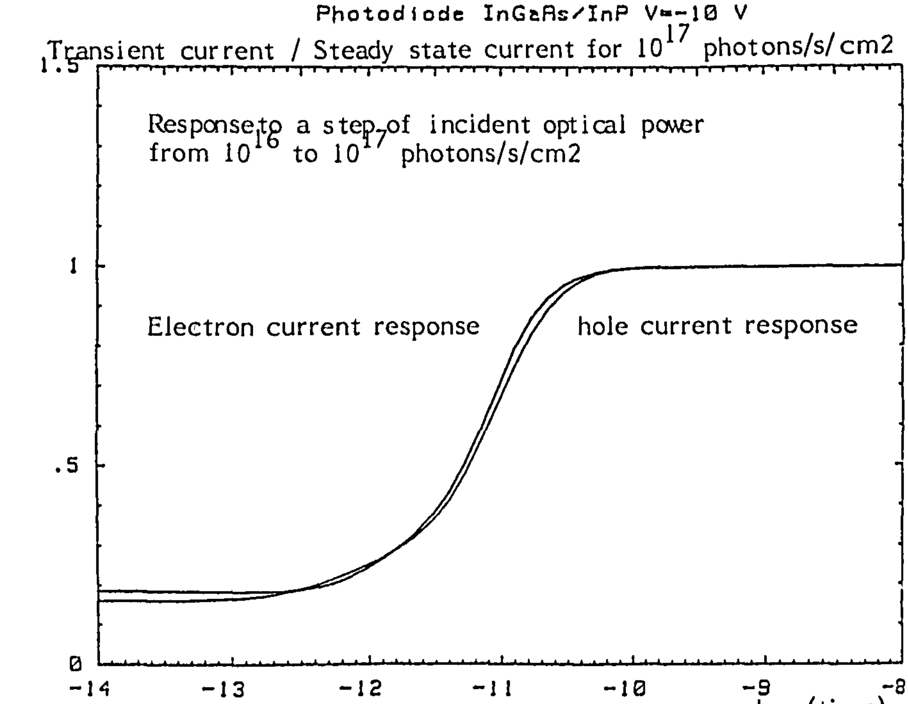

Fig 5 Electron and hole currents

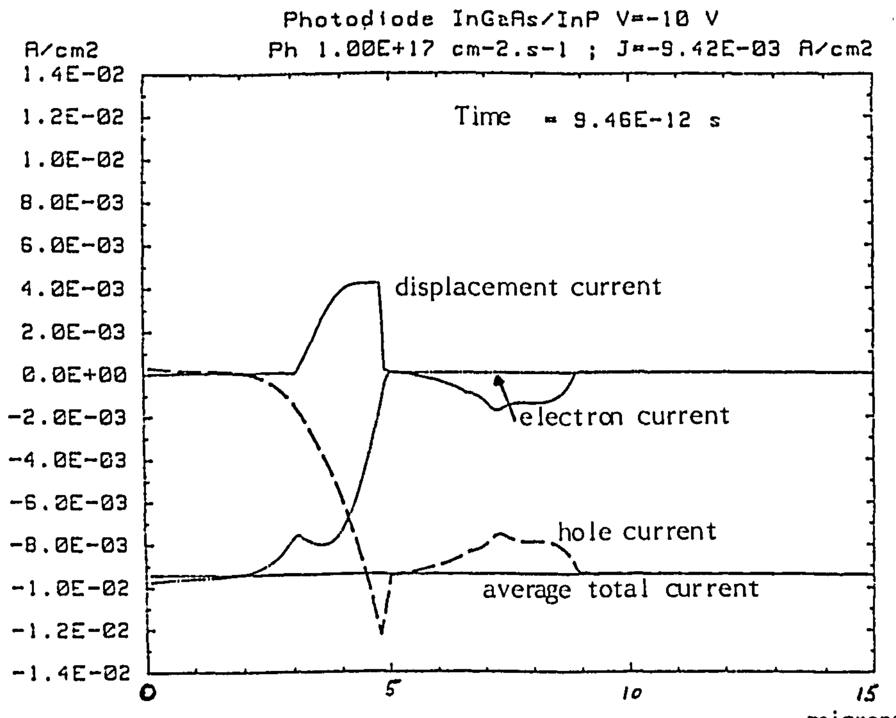

Fig 6 Displacement and conduction current distributions

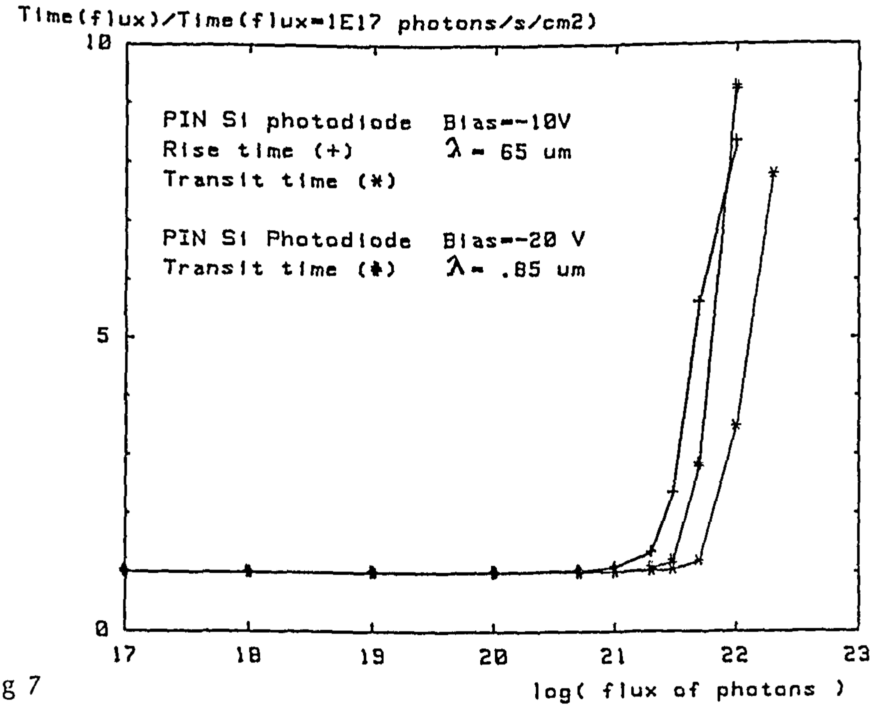
Time(flux)/Time(flux=1E17 photons/s/cm2)
10
5
0
PIN Si photodiode Bias=-10V
Rise time (+) λ= 65 um
Transit time (*)
PIN Si Photodiode Bias=-20 V
Transit time (*) λ= .85 um
17
18
19
20
21
22
23
log(flux of photons)

Fig 7

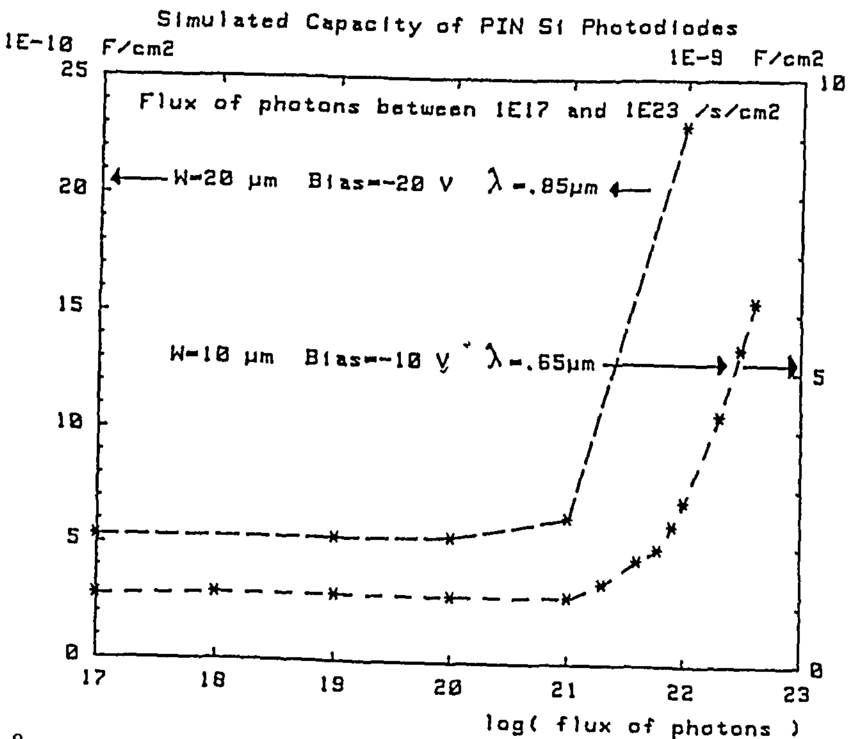
Simulated Capacity of PIN Si Photodiodes
1E-10 F/cm2
1E-9 F/cm2
25
20
15
10
5
0
10
5
0
Flux of photons between 1E17 and 1E23 /s/cm2
W=20 μm Bias=-20 V λ=.85μm
W=10 μm Bias=-10 V λ=.65μm
17
18
19
20
21
22
23
log(flux of photons)

Fig 8

Simulated rise time of Si PIN photodiode is reported on Fig 7 over several decades of optical power. As could be expected the rise time considerably increases for optical powers above the threshold of high injection conditions.

A cheaper CPU time evaluation of the rise time is now discussed.

VI- TRANSIT TIME AND CAPACITY OF PHOTODIODES

Transit time across the lightly doped region can easily be computed knowing the electric field distribution and carrier mobilities versus doping concentration and electric field (8,6).

As it was earlier discussed the low electric field area lowers drift velocity especially if the potential drop occurs in low mobility areas (highly doped layers or InP material).

Evolution of the transit time versus optical power agrees with the evolution of the simulated rise time as shown on Fig 7, although the computed rise time increases faster than the transit time.

The time response of the device is also affected by the RC constant (R=load, C capacity of the device).

For low optical power the capacity can be estimated since the two highly doped regions can be approximated to two plates separated by a depleted region (the intrinsic layer) of given dielectric permittivity.

Such an approximation no longer holds when the carrier densities in the lightly doped region are equivalent to those of the highly doped region.(Fig 3)

For high optical power the electric field distribution can be looked at as corresponding to two junctions (Fig 1).The corresponding space charge region is then smaller than the width of the lightly doped area. Therefore it could be expected that the overall capacity increases with increasing optical power.

An accurate computation of the capacity of the photodetectors is performed. The local variation of the electric charges and of the displacement current are taken into account between two close bias, keeping the optical generation constant.Capacity increases with optical power as it is showned on Fig 8

VII- CONCLUSION

Steady and transient simulation of Si and GaInAs PIN photodiodes show the influence of optical power over time response, sensitivity and linearity.

Under high injection, the photodetectors exibit far greater response time than they have under the low optical power for which they were designed.

An optimum between the expected signal to noise ratio improvement in heterodyne detection and a low enough response time, to keep up with the desired bit rate, can be found.

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Analysis and simulation of semiconductor devices

Table I

Schematic representation of Si PIN photodiodes

Layer	P^+	υ	N^+
$N_D^+ - N_A^-$	-10^{17}	10^{14}	10^{17}
width µm	.5	10 or 20	130
μ_n $cm^2/V/s$	700	1330	700
μ_p $cm^2/V/s$	225	495	225
$\tau_n = \tau_p$ (s)	10^{-9}	10^{-6}	10^{-9}

Table II

Schematic representation of GaInAs/InP photodiode

Layer	p^+	Erf	n^-	n^-	n^+
Material	GaInAs			InP	
Nc cm^{-3}	$2\ 10^{17}$			$5.4\ 10^{17}$	
Nv cm^{-3}	$7.6\ 10^{18}$			$1.3\ 10^{19}$	
Ki (eV)	4.52			4.04	
Eg (eV)	0,75			1.35	
ϵ_r	13,4			12.4	
Absorption coefficient 1,5µm	$7\ 10^3\ cm^{-1}$			Transparent	
$N_D^+ - N_A$	$-2\ 10^{18}$		10^{15}	10^{16}	10^{18}
$\mu_n cm^2/V/s$	5000	variation in erf Diffusion length of 0,5 µm	10000	4100	2400
$\mu_p cm^2/V/s$	130		300	150	80
$\tau_n = \tau_p$ (s)	10^{-11}		10^{-6}	10^{-6}	10^{-9}
(Width µm)	2	1	2	4	140