Final Project - Mesa structure high speed UTC-PD

ECE530 Introduction to Advanced Electronics & Optoelectronics
Michael Benker
Project Specification

• Construct an Atlas model for a mesa UTC photodetector.

Please find:

• (1) The x, y composition for lattice matched 1.1Q and 1.4Q.

• (2) Find I-V curve (reverse, forward biased) without light.

• (3) Find the PD impulse response when biased at -3 volt. To mitigate nonlinear effect, use small optical input.

• (4) find the frequency response of the PD.
**Structure Layer Definition**

**Base InP wafer:** semi-insulating InP (Fe)

<table>
<thead>
<tr>
<th>Top down layer structure:</th>
<th>1. 500A InGaAs Zn: 2e19 (p-contact)</th>
<th>10. 6000A InP Si : 1e16 (collector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. 1000A InP Zn: 1.5e18 (e-diffusion block)</td>
<td>11. 1000A InP Si: 1e18</td>
<td></td>
</tr>
<tr>
<td>3. 150A 1.1Q Zn: 2e18 (band smooth)</td>
<td>12. 9000A InP Si: 1e19</td>
<td></td>
</tr>
<tr>
<td>4. 150A 1.4Q Zn: 2e18 (band smooth)</td>
<td>13. 1000A 1.1Q Si: 1e19 (n-contact)</td>
<td></td>
</tr>
<tr>
<td>5a. 1000A InGaAs Zn: 2e18 (absorber)</td>
<td>14. 2500A InP Si: 1e19</td>
<td></td>
</tr>
<tr>
<td>5b. 1500A InGaAs Zn: 1e18 (absorber)</td>
<td>15. SI-substrate InP Fe</td>
<td></td>
</tr>
<tr>
<td>5c. 1500A InGaAs Zn: 5e17 (absorber)</td>
<td>(semi-insulating)</td>
<td></td>
</tr>
</tbody>
</table>
| 6. 1000A InGaAs Si : 1e16 (absorber) | Compositions (x,y):
| 7. 150A 1.4Q Si : 1e16 (band smooth) | \( \text{In}_x \text{Ga}_{1-x} \text{As} \ (x = 0.532) \) \( \text{In}_{0.532} \text{Ga}_{0.468} \text{As} \)
| 8. 150A 1.1Q Si : 1e16 (band smooth) | 1.4Q \ Lattice matchd (to InP) InGaAsP with bandgap corresponding to 1.4 micron photon wavelength \\
| 9. 500A InP Si: 1e17 (cliff) | 1.1Q \ Lattice matchd (to InP) InGaAsP with bandgap corresponding to 1.1 micron photon wavelength |
(1) The x, y composition for lattice matched 1.1Q and 1.4Q

Lattice matched (to InP) InGaAsP with bandgap corresponding to photon wavelength

- \( E_g = \frac{hc}{\lambda} = (4.135 \times 10^{-15} \text{ eV} \cdot \text{s}) \cdot (3 \times 10^8 \text{ m}^2/\text{s})/\lambda \)
- \( E_{g\text{InGaAsP}}(y) = 1.35 - 0.775y + 0.149y^2 \text{ (eV) (at 298K)} \)
- Lattice-Matched to InP: \( x = \frac{0.1894y}{0.4184-0.013y} \)

\( 1.4Q: \)

- 1.4 micron photon wavelength
- \( E_{g\text{InGaAsP}} = 0.8861 \text{ eV} \)
- \( y = 0.6909 \)
- \( x = 0.3196 \)

\( 1.1Q: \)

- 1.1 micron photon wavelength
- \( E_{g\text{InGaAsP}} = 1.1277 \text{ eV} \)
- \( y = 0.3048 \)
- \( x = 0.1393 \)
Structure in ATLAS

mesh auto
x.m l=-75 Spac=3
x.m l=-45 Spac=3
x.m l=-20 Spac=2
x.m l=20 Spac=2
x.m l=45 Spac=3
x.m l=75 Spac=3

# n-contact region to substrate
region bottom thick = 0.1 material = InGaAsP NY = 4 x.comp=0.1393 y.comp = 0.3048 donor = 1e19
region bottom thick = 0.25 material = InP NY = 4 donor = 1e19
region bottom thick = 2.0 material = InP NY = 4

#above n-contact region bottom-up
region top thick = 0.9 material = InP NY = 8 donor = 1e19
region top thick = 0.1 material = InP NY = 8 donor = 1e18
region top thick = 0.6 material = InP NY = 8 donor = 1e16
region top thick = 0.05 material = InP NY = 8 donor = 1e17

#band smooth
region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.1393 y.comp = 0.3048 donor = 1e16
region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.3196 y.comp = 0.6909 donor = 1e16

#absorber
region top thick = 0.1 mat = InGaAs NY = 8 x.comp=0.532 donor = 1e16
region top thick = 0.15 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 5e17
region top thick = 0.15 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 1e18
region top thick = 0.1 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 2e18
region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.3196 y.comp = 0.6909 acceptor = 2e18
region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.1393 y.comp = 0.3048 acceptor = 2e18
region top thick = 0.1 material = InP NY = 8 acceptor = 1.5e18
region top thick = 0.05 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 2e19

#etch
region mat = air x.min=20 x.max = 75 y.max = 0.0 NY = 3
region mat = air x.min = -75 x.max = -20 y.max = 0.0 NY = 3

#electrode
electrode name=gate x.min = -20 x.max = 20 y.max = 0
electrode name=np x.min=45 x.max=75 y.max = 0 y.min = 0
electrode name=np x.min=-75 x.max=-45 y.max = 0 y.min = 0

Department of Electrical and Computer Engineering
(2) Find I-V curve (reverse, forward biased) without light
Simulating Beam

Photogeneration Rate: number of electrons generated in the device due to absorption of photons. ✓

 Beam ATLAS Code (one intensity level):
  • beam num=1
  x.origin=0 y.origin=3
  angle=270
  wavelength=1.550
  min.window=-15
  max.window=15
  • ……
  • solve vgate=-3.0
  • solve b1=0.1
  outf=sol_hswgpd.str
  master onefile
Light Impulse in ATLAS

*Light Impulse* \( L[t] = u[t] - u[t-T] \)

**Photo-current Response**

```
solve vgate=-3.0
LOG off
LOG outf=transient_mb.log
SOLVE B1=1.0 RAMPTIME=1E-9 TSTOP=1E-9 TSTEP=1E-11
SOLVE B1=0.0 RAMPTIME=1E-9 TSTOP=20E-9 TSTEP=1E-11
tonyplot transient_mb.log
```
Frequency Response: Using ATLAS
Frequency Response: Method #2

MATLAB file import, plot

% Michael Benker
% ECE530 Final Project
% This program imports data exported from a Tonyplot and calculates the
% frequency response.
clc; clear all; close all; clf;

TonyPlotData = importdata('exporttransientresponse1.dat'); % exported data file from Tonyplot

TransientTime = TonyPlotData.data(4:21,1);
PhotoCurrent = TonyPlotData.data(4:21,2);
NewTimeAxis = linspace(TransientTime(1),TransiantTime(10),100);
Interpolate = interp1(TransientTime, PhotoCurrent, NewTimeAxis);
Conclusions

1. The x and y composition for InGaAsP matched to InP were calculated using formulas and a short MATLAB program. ✓

2. The UTC Photodetector structure was designed and simulated in ATLAS. ✓

3. An I-V curve for forward and reverse bias was simulated for the structure in ATLAS. ✓

4. A light beam is simulated into the structure in ATLAS and the photo-current generation is simulated to occur in the InGaAs layers. ✓

5. A light impulse is simulated using step functions in ATLAS and the current response from the light pulse is observed in ATLAS at -3V bias. ✓

6. Using the fourier command in ATLAS, the frequency response of the impulse is plotted in ATLAS. Simulations were also run in MATLAB to compare results. ✓
• InGaAsP matched to InP as function
• of wavelength program
• Michael Benker

Wavelength = 1.1e-6; %m
PlanckConstant = 4.135e-15; %eV*s
SpeedOfLight = 3e8; %m/s
InGaAsP_Bandgap = PlanckConstant...  
  *SpeedOfLight/Wavelength %eV

syms yComp
BandgapEquation = 1.35- 0.775*yComp ... +0.1498*(yComp)^2 == InGaAsP_Bandgap;
y = solve(BandgapEquation,yComp);
y = double(y(1,1))
x = 0.1894*y/(0.4184-0.013*y)

%Michael Benker  
%ECE530 Final Project  
%This program imports data  
%exported from a Tonyplot and  
calculates the  
%frequency response.  
clear; clear all; close all; clf;

X = importdata('transientin1.dat');  
Y = TonyPlotData.data(4:21,1);  
TransientTime = TonyPlotData.data(4:21,1);
PhotoCurrent = TonyPlotData.data(4:21,2);
NewTimeAxis = linspace(TransientTime(1),TransientTime(18),100);  
Interpolate = interp1(TransientTime, PhotoCurrent, NewTimeAxis);

%Interpolate = zeros(18,2);  
%Interpolate(:,1) = TransientTime;  
%Interpolate(:,2) = PhotoCurrent;

figure(1) %Plot Tonyplot data  
plot(TransientTime, PhotoCurrent)  
suptitle('Tonyplot Data Plot')  
xlabel('Beam Intensity')

figure(2)  
plot(Fdomain)  
xlabel('Frequency')  
ylabel('Magnitude')  

freqz(Interpolate)  
Fdomain = pwelch(Interpolate);
ATLAS Code – IV Curves

- #Materials
  - mobility material = InP muns = 4917.0 mups = 4e3
  - vsatp = 4.6e7 ecrtn = 4e3 ecrtp = 4e3 gammas = 4 gamma = 4
  - mobility material = InGaAs mun = 1159.0 mups = 330.0 vsatn = 2.5e7
  - vsatp = 0.5e7 ecrtn = 4e3 ecrtp = 4e3 gamman = 4
gammap = 4
  - mobility material = InGaAsP mun = 4600.0 mups = 1500.0 vsatn = 2.6e7
  - vsatp = 0.6e7 ecrtn = 4e3 ecrtp = 4e3 gamman = 4
gammap = 4
  - models fldmob sft opt sft fermidrac connopt print EVSATMOD = 1

- #tech
  - region mat = air x.min = 20 x.max = 75 y.min = 0.00 y.max = 0.00
  - region mat = air x.min = -75 x.max = -20 y.min = 0.00 y.max = 3.00

- #electrode
  - electrode name = gate x.min = -20 x.max = 20 y.min = 0.00 y.max = 0.00
  - electrode name = np x.min = 45 x.max = 75 y.min = 0.00 y.max = 0.00
  - electrode name = np x.min = -75 x.max = -45 y.min = 0.00 y.max = 0.00
  - contact name = gate resistance = 0.1
  - #interface y.min = 1.9 y.max = 1.4 x.min = -1 x.max = 1
  - thermionic = true tunnel = true s = true

- solve x.gnu = 0.1 vstep = 0.1 vfinal = 3 name = "gate"
tonyplot hs wg pd f log
- log off
- solve init
- #beam nums = 1 x.origin = 0.0 y.origin = 0.0 angle = 90.0
  - wavelength = 0.550 tayos = 100 sigma = 1.0 gaussian periodic
  - stdout = sol hs wgp d str
  - LOG out = hs wg pd r log
  - save x.gnu = 0.1 vstep = 0.1 vfinal = 3 name = "gate"
tonyplot hs wg pd r log
- log off

- output band param photogen opt.intens con.band val band
  - e mobility h mobility band param photogen opt.intens recomb u sth u aug u rad flowlines
  - save stdout = hs wg pd str
  - tonyplot hs wg pd str
  - #tonyplot sol hs wgp d str
  - quit

- solve x.gnu = 0.1 vstep = 0.1 vfinal = 3 name = "gate"
tonyplot hs wg pd f log
- log off
- solve init
- #beam nums = 1 x.origin = 0.0 y.origin = 0.0 angle = 90.0
  - wavelength = 0.550 tayos = 100 sigma = 1.0 gaussian periodic
  - stdout = sol hs wgp d str
  - LOG out = hs wg pd r log
  - save x.gnu = 0.1 vstep = 0.1 vfinal = 3 name = "gate"
tonyplot hs wg pd r log
- log off

- output band param photogen opt.intens con.band val band
  - e mobility h mobility band param photogen opt.intens recomb u sth u aug u rad flowlines
  - save stdout = hs wg pd str
  - tonyplot hs wg pd str
  - #tonyplot sol hs wgp d str
  - quit

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solve \ b1=0.5

solve \ b1=1.05

taun0=20.e

solve \ b1=0.25

NY = 10

x.ml l=45 Spac=3

# absorber

NY = 4
donor =

solve \ b1=0.2

region bottom thick = 0.25 material =

NY = 8

solve \ b1=0.2

region top thick = 0.1 material = InGaAs NY = 8 x.comp=0.532 acceptor = 1e18

region top thick = 0.15 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 5e17

region top thick = 0.15 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 1e18

region top thick = 0.1 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 2e18

region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.3196 x.comp = 0.6909 acceptor = 2e18

region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.1393 y.comp = 0.3048 acceptor = 2e18

region top thick = 0.1 material = InP NY = 8 acceptor = 1.5e18

region top thick = 0.05 mat = InGaAs NY = 8 x.comp=0.532 acceptor = 2e19

#etch

mat = air

x.min =20 x.max =75 y.max =0.0 NY =3

region mat = air x.min=-75 x.max =-20 y.max =0.0 NY =3

#electrode

electrode name=gate x.min =-20 x.max=20 top
electrode name=x.p min=45 x.max=75 y.max =75 x.max =45 y.max =0 y.min =0

contact name=gate resistance =0.1

#interface

y.min=-1.9 y.max=1.4 x.min=-1 x.max=1

thermionic=true tunnel=false ss=true

#Materials

material material=InGaAsP taum0=20.e-9 taup0=33e-9\align=0.4

material=InGaAs taum0=0.7e-9 taup0=33e-9 \real.index=3.43 imag.index=0.2

material=InP taum0=2e-9 taup0=33e-9 \align=0.4 \real.index=3.17 imag.index=0

# model

mobility material = InP mumu=4917.0 mu = 150.0 vsatn = 2.6e7

vsatp = 6.6e7 ecritn = 1e3 ecrirp = 4e3 gamman = 4 gamman = 4 gammap = 1

mobility material = InGaAs mumu=11599.0 mu = 331.0 vsatn = 2.5e7 vsatp = 0.5e7 ecritn = 3e3 ecrirp = 4e3 gamman = 4 gammap = 1

mobility material = InGaAsP mumu=4600.0 mu = 150.0 vsatn = 2.6e7 vsatp = 0.6e7 ecritn = 3e3 ecrirp = 4e3 gamman = 4 gammap = 1

models flmob sfr opt ferminicron connmob print

EVSATMOD=1

beam mumu=1.x.origin=0 y.origin=3 angles=270

wavelength=1.550 min.window=15 max.window=15

# solving

solve init

outf= sol_hswgpd.str

LOG outf=hs_wg_pd_r.log

# output band param photogen opt.intens cons.band val band e.mobility h.mobility band param photogen opt.intens recomb u.srh u aug u rad flowlines

solve outf=hs_wg_pd.str

tonyplot hs_wg_pd.r.log

# quit
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# ECE530 Advanced Electronics/Optoelectronics

# Final Project: UTC Photodetector

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## ATLAS Code – Frequency Response

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- `#n-contact region to substrate`
- `region bottom thick = 0.1 material = InGaAsP NY = 4 x.comp=0.1393 y.comp = 0.3048 donor = 1e19`
- `region bottom thick = 0.25 material = InP NY = 4 donor = 1e19`
- `region bottom thick = 2.0 material = InP NY = 4`

- `#above n-contact region bottom-up`
- `region top thick = 0.9 material = InP NY = 8 donor = 1e19`
- `region top thick = 0.1 material = InP NY = 8 donor = 1e18`
- `region top thick = 0.6 material = InP NY = 8 donor = 1e16`
- `region top thick = 0.05 material = InP NY = 8 donor = 1e17`

- `#band smooth`
- `region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.1393 y.comp = 0.3048 donor = 1e16`
- `region top thick = 0.015 material = InGaAsP NY = 10 x.comp=0.3196 y.comp = 0.6909 donor = 1e16`

---

- SOLVE B1=1.0 RAMPTIME=1E-9 TSTOP=1E-9 TSTEP=1E-12
- SOLVE B1=0.0 RAMPTIME=1E-9 TSTOP=20E-9 TSTEP=1E-12

- tonyplot transient_mb.log
- #solve b1=0.01 ss.phot ss.light=0.001 beams=1 freq=1e5
- #solve b1=0.01 ss.phot ss.light=0.001 beams=1 freq=1e16
- outf=ss_hwsgpd.str master onefile
- log off

- log outf=mbutcpd_fdom2.log
- FOURIER INFILE=transient_mb.log
- OUTFILE=mbutcpd_fdom2.log T.START=0 T.STOP=20E-9 INTERPOLATE
- tonyplot mbutcpd_fdom2.log

- LOG off

- output band param ramptime TRANS.ANALY photogen opt.intens con.band val.band.c mobility h.mobility band.param photogen opt.intens recomb u.srh u.aug u.rad flowlines

- save outf=hs_wg_pd.str
- #LOG outf=mbutcpd_fdom.log
- tonyplot hs_wg_pd.str

- quit

---

# Materials

- material=InGaAsP
- taun0=2.0e-9 taup0=33e-9
- align=0.4 real.index=3.4 imag.index=0

- material=InGaAsP
- taun0=0.7e-9 taup0=33e-9
- real.index=3.43 imag.index=0.2

- material=InP
- taun0=2.0e-9 taup0=33e-9
- align=0.4 real.index=3.17 imag.index=0

- #model

- mobility material=InP num=4917.0 mups=150.0 vsatn = 2.6e7 vntn = 0.6e7 ecrtn=1e3 ecritp=1e3 gamman=1
- mobility material=InGaAsP muns=11599.0 mups=331.0 vsatn = 2.5e7 vntn = 0.5e7 ecrtn=1e3 ecritp=1e3 gamman=1
- mobility material=InGaAs muns=11599.0 mups=150.0 vsatn = 2.6e7 vntn = 0.6e7 ecrtn=1e3 ecritp=1e3 gamman=1

- models fdlmob s6h opt fermiarc comob print EVSATMOD=1
- beam num=1 x.origin=0 y.origin=5 angle=270 wavelength=1550 min.window=15 max.window=15

- #waveform beams=1 amplitude=1e3 frequencies=5e9 number=1 periods=1000 simu1
- solving
- METHODS HALFIEMPL
- solve init
- outf = sol_hwsgpd.str
- LOG off=hs_wg_pd_r.log
- solve vgate=3.0
- LOG off
- LOG outf=transient_mb.log

---

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References

• ATLAS TCAD Manual
• Swiss Federal Institute of Technology Zurich – Prof. Jaeckel-
  http://people.ee.ethz.ch/~fyuriy/oe/
• SMU Photonic Study Group 2003
• https://www.silvaco.com