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# Capacitance-Voltage Fitting Algorithm for Doping Profile Characterisation of Mesa Diodes Using MATLAB

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**Abstract:** In this study, a capacitance-voltage fitting algorithm was developed using four region approximations and fitted against three GaAs mesa diodes. Doping and electric field profile measured and fitted are presented using MATLAB based programming. Results of 4-regions approach gave a better fitting in all the diodes compared to 3-regions approximation. It also showed good approximation to the mesa diodes measured C-V by using higher number of approximated region.

**Key words:** gallium arsenide, nanoparticles, semiconductor, profiling, programming, punchthrough

## INTRODUCTION

Nowadays, even with controlled doping of semiconductors, problems such as auto-doping may interfere and the doping profile may not turn out as designed. Other problems include defects from diffusion, ion implantation and lithography process (Prabket, J., et al., 2012). Thus, reliable information on doping profile of semiconductor p-n and p-i-n diodes is useful to understand diode operation and be in control of the diode design or fabrication process. Other researchers have reported use of capacitance-voltage (C-V) to determine semiconductor parameters such as carrier concentration (Tschanz, S., et al., 2007), carrier mobility and carrier compensation, particularly in III-V compound devices (O'Regan, T.P. and P.K. Hurley, 2011; Khamari, S.K., et al., 2011). This technique is used widely in the university and semiconductor laboratories to evaluate and enhance performance of new design structures and materials of diodes.A numerical simulation is required to analyse the C-V results in order to extract doping and electric field profiles of semiconductor diodes.MATLAB has vast computational potential and is usually available in most research organization. This paper presents a MATLAB based simulation of C-V fitting algorithm to determine and approximate doping and electric field profile of mesa diodes withinformation on doping profile and area of the diodes.

### *C-V Experimental Setup:*

C-V measurements were done in the dark and at room temperature usingHP 4275 LCR meter with an AC voltage signal of ~50mV and a frequency of 1MHz. The measurements were performed on three mesa diodes with radius of 100μm, sample A, B and C respectively. The diodes described are linearly graded GaAs PIN mesa diodes grown and fabricated in Sheffield University, UK.

### *C-V Fitting Algorithm:*

Doping profiles of the diodes grown were extracted from a capacitance-voltage (C-V) fitting by solving the one dimensional Poisson’s equation (Sze, S.M., 1981),

$$\frac{dE}{dx} = -\frac{qN}{\varepsilon_o \varepsilon_r} \quad (1)$$

$$E = -\int \frac{qN}{\varepsilon_o \varepsilon_r}\, dx \quad (2)$$

where $N$ is the doping concentration, $\varepsilon_o$ is the permittivity of free space and $\varepsilon_r$ is the relative permittivity of the device material. This relates electric field, $E$ and the width of depletion region, $x$ with the doping concentration, $N$. Therefore the change in the electric field is simply the slope of the triangle and is given by equation (1). The electric field distribution is obtained through the integration of the charge profile in the semiconductor over the variable, $x$ as in equation (2).Using simple geometry, the maximum electric field, $E_{Max}$can be approximated by the following equation:

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$$E_{Max} = -\frac{qN_D x}{\varepsilon_0 \varepsilon_r} \qquad (3)$$

The maximum electric field, $E_{Max}$is a critical parameter in the design of a reverse bias junction. Given the region thicknesses and doping levels, the device punch through voltage is calculated accordingly. Punch through voltage refers the point at which the depletion layer broke through the initial layers and into the adjacent layer. Figure 1 shows the punch through in MATLAB code while Figures 2 depict the charge distribution and electric field under reverse bias conditions.

```
%%
%Punchthrough 3 sided Vt =6.1426 V
p= (-N3*d - N2*w)/N1;
E1 = q*N1*p/Ep;
E2 = -q*N3*d/En;
Vt=0.5*((E1*(p+w)) + (E2 *(w+d))) ;

%%
%Punchthrough 2 sided Vd = 2.4724 V
Vd = ((0.5*q*N2*w^2)/Ei) * ( N2/N1 - 1 );
```

**Fig. 1:** MATLAB code to calculate the punch-through voltage.

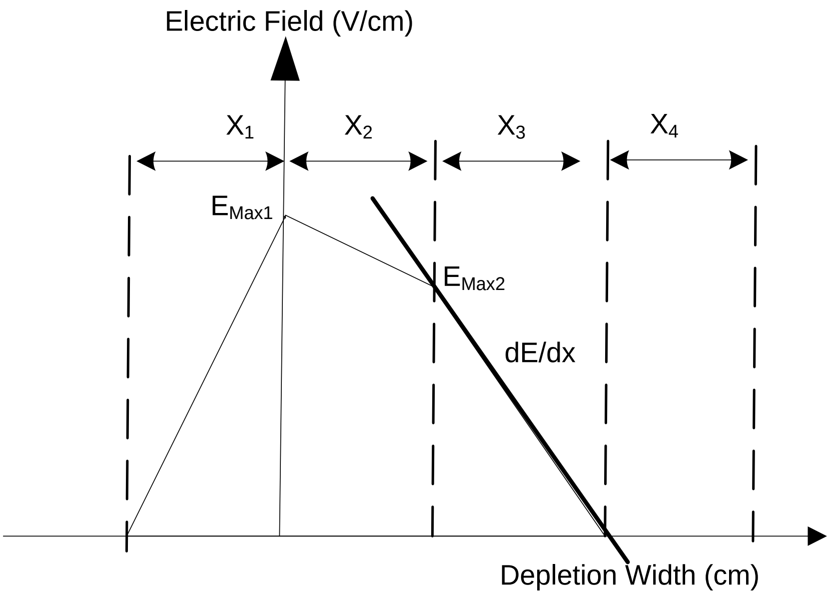



**Fig. 2:** Electric field, *E* profile and punch-through voltage for third region before the fourth region is depleted.

From Figure 2, each region have doping concentrations of $N_1$, $N_2$, $-N_3$and $-N_4$ (negative sign indicates n-type doping), respectively, while $X_1$, $X_2$, $X_3$and $X_4$ denote the depletion width of each region. The initial concentration of each region and the depletion width of the intrinsic region are first assumed based on the information of the growth parameters. Finally, the values of $X_1$, $X_2$ and $X_3$ are under depletion width approximation, capacitance can be calculated as in equation (9).

$$C = \frac{\varepsilon A}{W} F/cm^2 \qquad (9)$$

where $W$ is the total depletion width $(X_1 + X_2 + X_3 + X_4)$ and A is the area of the device. Once the doping concentration and the depletion width of each region were found, the electric field profile is then plotted to observe the distribution of electric field in the intrinsic region. This C-V fitting technique has been adopted and extended from previous work (Tan, C.H., 2002) by extending the three-sided depletion region assumption to four sided regions intended to provide a better fitting of the measured C-V values.

Figure 3 shows the extended algorithmprocesswhile Figure 4 is the MATLAB code representation. The process is repeated by adjusting the parameters until the calculated and fitted C-V values are within adequate levels of error. The fitting of each set of adjusted parameters are measured by mean squared error and the percentage norm error between the measured values and the simulated values. As the mean squared error approach zero, it shows the accuracy of the fitting.Meanwhile, when the percentage norm error approaches zero, the fitted values are closer to the measured values.

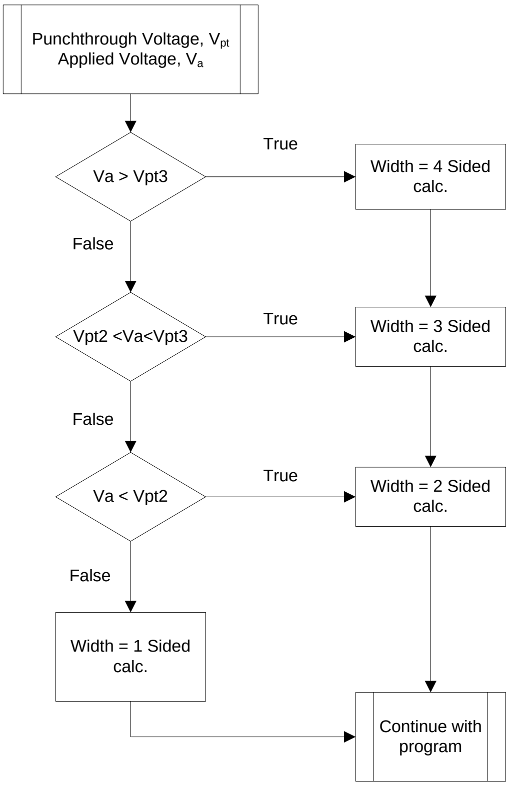


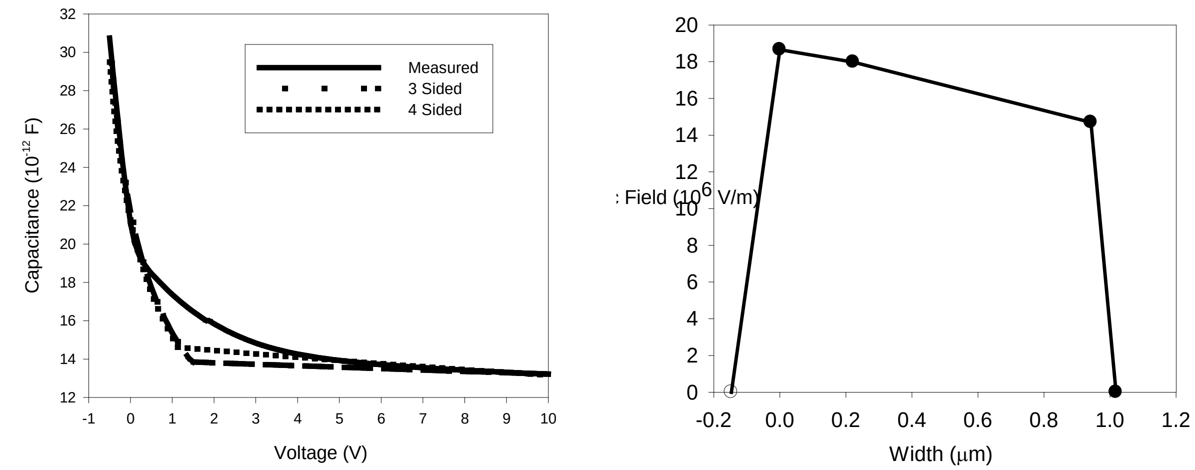

**Fig. 3:** MATLAB code to calculate the depletion width of 2, 3 and 4-region approximation.

```
for j = 1:numel(Va);
V(j,1)= Va(j,1)+ Vbi;

if (V(j,1)> Vt)

  a (j,1)= (N1/Ep) * (1 - ((N1*Ex)/(N4*Ep)) );
  b (j,1)= (2*N1/Ep) * ((w+d)-(((N2*w/Ei) + (N3*d/En) ) *(Ex/N4)) );
  c (j,1)= ((((N2*w/Ei) + (N3*d/En))^2)/(N3/En)) + ((N2*w^2/Ei)+ (N3*d^2/En)) + (2*N2*w*d/Ei)- (2*V(j,1)/q);
  x1 (j,1)= (-b(j,1) + (b(j,1)^2 - (4*a(j,1)*c(j,1)))^0.5 ) / ( 2*a(j,1) );     %dp
  x2 (j,1)= w;                                       %di
  x3 (j,1)= d;
  x4 (j,1)= - ( (N1*x1(j,1)/Ep)+(N2*w/Ei) + (N3*d/En) ) * (Ex/N4);      %dn

elseif (Vd < V(j,1)< Vt)

  r (j,1)= (N1/Ep) * (1 - ((N1*En)/(N3*Ep)) );
  s (j,1)= (2*N1*w/Ep) * (1 - ( (N2*En) / (N3*Ei) ) );
  t (j,1)= ((N2*w^2)/Ei) * (1 - (N2*En)/(N3*Ei) ) - (2*V(j,1)/q);
  x1 (j,1)= (-s(j,1) + (s(j,1)^2 - (4*r(j,1)*t(j,1)))^0.5 ) / ( 2*r(j,1) );     %dp
  x2 (j,1)= w;                                       %di
  x3 (j,1)= - ( (N2*w/Ei) + (N1*x1(j,1)/Ep) ) * (En/N3);      %dn
  x4 (j,1)= 0;
else

   e (j,1)= -(2*V(j,1)*Ei / (q*N2)) / ( 1 - (N2/N1)*(Ep/Ei) );    %di^2
   x2 (j,1)= sqrt(e(j,1));
   x1 (j,1)= - (N2/N1) * (Ep/Ei) * x2(j,1)    ;              %dp
   x3 (j,1)= 0;                                   %dn = 0
   x4 (j,1)= 0;

end
width (j,1) = x1(j,1) + x2(j,1) + x3(j,1)+ x4(j,1);
```

**Fig. 4:** MATLAB code to calculate the depletion width of 2, 3 and 4-region approximation.

***MATLAB Based Simulation Results:***

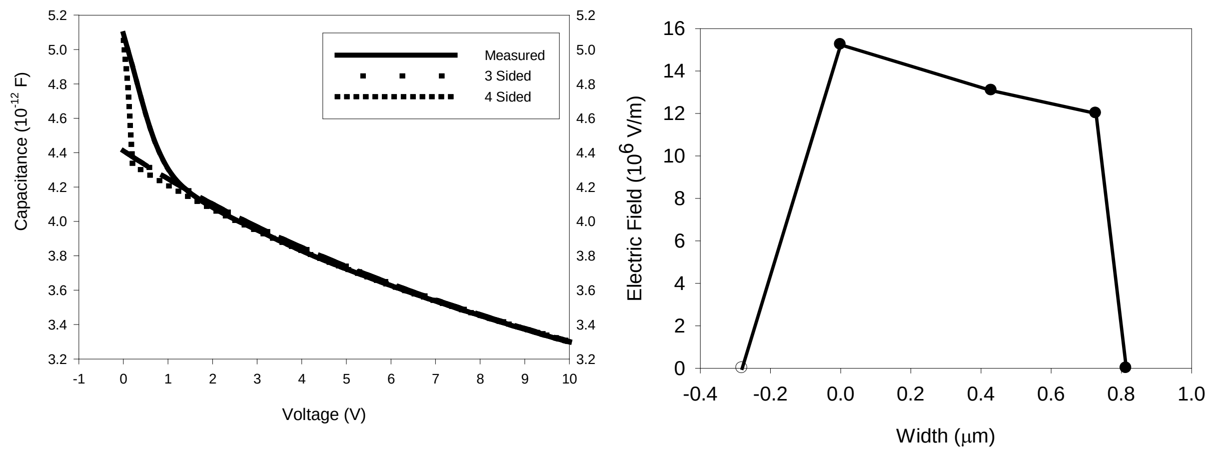
The C-V fittings were performed on all three mesa diodes. The dielectric constant for GaAs is 13.1 [5] and built-in voltage, $V_{bi}$, was assumed to be 1V. Figure 5 (a) shows the results of C-V fitting with the best fit performed on sample Awhile Figure 5 (b) shows theelectric field profile of sample A using 4-regionapproximation.




(a) (b)

**Fig. 5:** (a) Comparison C-V of A (b) electric field profile of A using 4-region

It can be observed that the 4-sided approximation gave a better C-V fitting of the C-V measured compared to the 3-sided fitting. Figure 6 (a) shows the results of C-V fitting with the best fit using 4-region assumption for B diode in reverse bias. The capacitance is simulated with applied voltage of 0V to 10V in reverse bias.




(a) (b)

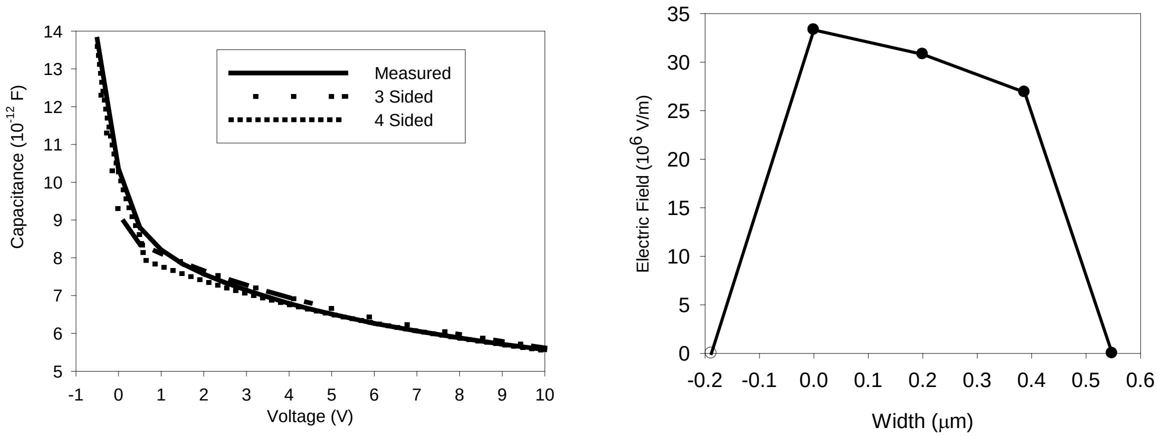
**Fig. 6:** (a) Comparison of C-V plot of B and (b) electric field profile of B.

Figure 7(a) shows the C-V characteristics of C diode and (b) shows the electric field profile of C utilizing 4-regions assumption. Figure7(a) shows that the 4-region approximation gives a better fitting of the C-V and expected to have better estimated value. The percentage norm error and mean squared error, MSE from Figure 3, 4 and 5 are calculated and the results are discussed in the next section.

***Discussion:***

The fitted values of doping density and i-region thickness are tabulated in Table 1, 2 and 3 for diodes A, B and C, respectively. For diodes A in Table 1, it can be observed that the set of parameters using 4-region approximation gives the minimum MSE and percentage norm error when compared with the measured C-V. Therefore, this proves that 4-region approximation gives the better C-V fitting. However, the relative difference between 4-region approximation and measured C-V values is only 5.34% compared to the 3-region approximation which is 6.36%. The relative difference and MSE of the two approaches is 2.68% and $1.6x10^{25}$

cm$^{-3}$respectively. This is considered to give a relatively small improvement to the C-V fitting. The extracted i-region thickness decreased by 0.088μm from 1.03μm as well as the doping concentration in all regions. This is expected as the i-region is represented by two regions instead of one which gives a better doping profile approximation.




(a) (b)

**Fig. 7:** (a) Comparison of C-V plot of C and (b) electric field profile of C.

**Table 1:** Calculated doping density and i-region thickness of A.

| No. of approximated regions | i-region thickness | | p-region concentration | i-region concentration | | n-region concentration | (%) | MSE ($10^{-25}$) |
|---|---|---|---|---|---|---|---|---|
| | w (μm) | d (μm) | $N_p$ ($10^{22}$ cm$^{-3}$) | $N_w$ ($10^{22}$ cm$^{-3}$) | $N_d$ ($10^{22}$ cm$^{-3}$) | $N_n$ ($10^{22}$ cm$^{-3}$) | | |
| 4-region | 0.222 | 0.720 | 9.2 | -0.22 | -0.33 | -14 | 5.34 | 6.32 |
| 3-region | 1.03 | | 23 | -0.33 | | -23 | 6.36 | 8.86 |

**Table 2:** Calculated doping density and i-region thickness of B

| No. of approximated regions | i-region thickness | | p-region concentration | i-region concentration | | n-region concentration | (%) | MSE ($10^{-25}$) |
|---|---|---|---|---|---|---|---|---|
| | w (μm) | d (μm) | $N_p$ ($10^{22}$ cm$^{-3}$) | $N_w$ ($10^{22}$ cm$^{-3}$) | $N_d$ ($10^{22}$ cm$^{-3}$) | $N_n$ ($10^{22}$ cm$^{-3}$) | | |
| 4-region | 0.43 | 0.298 | 3.9 | -0.36 | -0.26 | -10 | 2.77 | 0.11 |
| 3-region | 0.79 | | 6 | -0.2 | | -5 | 3.40 | 0.17 |

Results from Table 2 shows that the 4-region approximation has a 2.77% relative difference as compare to 3.40% using the 3-region estimation. This again proves that 4-region had a better estimation of the C-V fitting algorithm. However, the fitting improvement is considered very small with MSE difference of 6 x $10^{-27}$.

**Table 3:** Calculated doping density and i-region thickness of C.

| No. of approximated regions | i-region thickness | | p-region concentration | i-region concentration | | n-region concentration | (%) | MSE ($10^{-25}$) |
|---|---|---|---|---|---|---|---|---|
| | w (μm) | d (μm) | $N_p$ ($10^{22}$ cm$^{-3}$) | $N_w$ ($10^{22}$ cm$^{-3}$) | $N_d$ ($10^{22}$ cm$^{-3}$) | $N_n$ ($10^{22}$ cm$^{-3}$) | | |
| 4-region | 0.20 | 0.187 | 12.7 | -0.9 | -1.5 | -12 | 2.01 | 0.207 |
| 3-region | 0.50 | | 16 | -1.15 | | -16 | 4.72 | 1.134 |

Finally, from Table 3, it can be seen that using the 4-sided region assumption, a percentage difference of 2.01% is achieved compared to 4.72% when using the 3-sided region assumption. As predicted, 4-region estimation provides an improved estimation of the C-V characteristics. Moreover, this set of variables gives much better MSE of 0.207x$10^{-25}$ compared to 1.134x$10^{-25}$. There may also be applications to investigate failure mechanisms such as radiation in doping profiles of semiconductor devices to improve design and material quality.

***Conclusion:***

In conclusion, from the results of comparing 3-region with 4-region approximation, it is shown that the values using the 4-sided approximation were in much closer agreement to the calculated values. The best fitting were performed on the C diode with mean squared error of $2.07x10^{-26}$ and percentage relative difference between measured and fitted C-V equal to2.01%. Other sets of parameter also give good fittings of the measured values however there seems to be only a slight improvement in mean squared error and the percentage relative difference. Nonetheless, in this case study it shows that a better fitting of the capacitance-voltage characteristics can be achieved by using MATLAB at a higher number of approximated region.

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## REFERENCES

Khamari, S.K., V.K. Dixit, T. Ganguli, S. Porwal, S.D. Singh, S. Kher, R.K. Sharma, and S.M. Oak, 2011. "Effect of 60Co γ-ray irradiation on electrical properties of GaAs epilayer and GaAs p-i-n diode," *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms,* 269: 272-276.

O'Regan, T.P. and P.K. Hurley, 2011. "Calculation of the capacitance-voltage characteristic of GaAs, In 0.53Ga 0.47As, and InAs metal-oxide-semiconductor structures," *Applied Physics Letters,* pp: 99.

Prabket, J., I. Srithanachai, S. Ueamanapong, A. Poyai, W. Titiroongruang, S. Niemcharoen, and P.P. Yupapin, 2012. "An improvement of electrical characteristics of PN diode by X-ray irradiation method," *Scientific Research and Essays,* 7: 1230-1236.

Sze, S.M., 1981. *Physics of Semiconductor Devices*, 2 ed.: John Wiley & Sons, Inc.,

Tschanz, S., J. Garcia and N. Haegel, 2007. "Modeling of cryogenic capacitance–voltage (C–V) profiling for the determination of minority doping concentration in blocked impurity band (BIB) detector structures," *Solid-State Electronics,* 51: 1062-1066.

Tan, C.H., 2002. "Measurements of excess avalanche noise in sub-micron Si and Al0.8Ga0.2As avalanche photodiodes," PhD thesis, University of Sheffield, Department of Electronic and Electrical Engineering.