CONF-980355--

NEW EXPERIMENTAL AND ANALYSIS METHODS IN I-DLTS*

S.U. Pandey^a, P. Middelkamp^b, Z. Li^c, and V. Eremin^d

^aWayne State University, Detroit, MI

^bBrookhaven National Laboratory, Upton, NY

^cLoffe Physico-Technical Institute, RAS, St. Petersburg, Russia

RECEIVED
APR 08 1998
OSTI

February, 1998

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

19980427 074

*This work was supported in part by the U. S. Department of Energy: Contract No. DE-AC02-76CH00016.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

New experimental and analysis methods in I-DLTS

S. U. Pandey (a), P. Middelkamp (b), Z. Li (c), and V. Eremin (d)

(a) *Wayne State University, Detroit, MI, USA*

(b) *Brookhaven National Laboratory, Upton, NY, USA*

(c) *Ioffe Physico-Technical Institute, RAS, St-Petersburg, Russia*

Abstract:

A new experimental apparatus to perform I-DLTS measurements is presented. The method is shown to be faster and more sensitive than traditional double boxcar I-DLTS systems. A novel analysis technique utilising multiple exponential fits to the I-DLTS signal from a highly neutron irradiated silicon sample is presented with a discussion of the results. It is shown that the new method has better resolution and can deconvolute overlapping peaks more accurately than previous methods.

1. Introduction

Microscopic defect analysis techniques are widely used in the study of deep level defects in semiconductors. Traditional Capacitance Deep Level Transient Spectroscopy (C-DLTS) was developed by Lang [1] and is a sensitive and straightforward to analyze temperature dependant spectroscopic technique to determine concentrations, energy levels, and capture rates of traps. Recently I-DLTS (current-DLTS) [2] has been shown to be promising method to analyze high resistivity silicon and to identify and correlate radiation induced deep levels with other properties of the semiconductor under study. This paper presents a new apparatus that increases the speed with which the I-DLTS signal is extracted over traditional methods. It will demonstrate a new analysis technique to increase the resolving power of the method.

2. Experimental Method and Results

Details of the BNL I-DLTS double boxcar system have been described in ref [2]. The new addition to the system is a digital oscilloscope (TDS 540) to record the current transient. The sample (Si. Pol. Oxygen 3×10^{15} O/cm³; RTA 3.8m; ETA 5hr) used in this study was a high resistivity p⁺/n/n⁺ diode irradiated to 1.03×10^{14} n/cm². A thermal scan of the sample was made and the I-DLTS transients at each temperature were recorded for further analysis. This allows one to compare the old double boxcar and new multi-exponential method as well as point out the future possibilities of this new experimental system.

The DLTS transient, typically an exponential in time, is usually fed into a dual-gate signal averager (double boxcar) which selects the emission rate window and improves the signal to noise ratio by averaging many transients allowing the detection of low concentration traps. The idea is to fully characterize the transient by sampling it at two discrete points in time along the exponential as seen in Figure 1. Notice that the transient is obviously non-exponential and is better characterized by two exponentials. The double boxcar I-DLTS signal in Figure 1 is equal to $V(t_1) - V(t_2)$, where $t_1 - t_2$ is typically referred to as the rate window, and the I-DLTS spectrum is generated by plotting this voltage difference versus temperature as seen in Figure 2. In Figure 2 we show the I-DLTS spectrum generated by

fitting single and double exponentials to the transients. As seen there is a significant difference between the two since single exponentials do not well characterize the transient. By varying t_1 in Figure 1 and determining the positions of the peaks in the I-DLTS spectrum in Figure 2 Arrhenius plots are generated to determine the energy and cross-sections of traps. The implicit assumption made when analyzing I-DLTS spectrums for energies and cross-sections is that the transient is exponential, an assumption which Figure 1 shows to be not always valid.

Replacing the double boxcar with a digital oscilloscope allows one to characterize the full transient (important in the presence of non-exponential signals arising from closely spaced traps or broad activation energies for emission) at no cost in time for acquiring the DLTS spectrum. The transient can then be analyzed for the presence of multiple exponentials and I-DLTS signals can be generated for each of the multiple exponentials. The time scale for a measurement is set by the wait for thermal equilibrium at each temperature step.

Access to all the points on the transient as opposed to two reduces the errors on the DLTS signal for the same data set as seen in Figure 3. The new method allows one to fit the transient at each temperature step to fully characterize it thus decreasing the errors on determining the level of the transient at a particular time with respect to the old method. With the new method only one temperature scan is necessary to fully characterize a sample as different rate windows are trivially generated once all the transients are fit as seen in Figure 4 giving the user a quick 3D graphical representation of the Arrhenius curves. Code to extract the energies and cross-sections of the traps seen in Figure 4 is straightforward. The method used in this paper is to look at the projections of Figure 4 in the temperature-time plane and fit the resulting curves as seen in Figure 5. The energy and cross-sections of the traps in Figure 5 are determined by the following equations:

$$\begin{cases} E_c - E_t \text{ (or } E_t - E_v) = \frac{\text{Slope}}{5.03} \text{ (eV)} \\ \sigma_n = 6.10 \times 10^{-22} \cdot \alpha \cdot 10^{-I} \end{cases}$$

where $E_c - E_t$ is the energy of the trap, σ_n is the cross-section in cm^2 , α is a constant which depends on the value of t_1 and t_2 used in Figure 1 (1.12 for $t_2=4t_1$), and I is the intercept of the curves in Figure 5. It should be noted that the curves in Figure 5 would be better fit should the points span a greater range. This just corresponds to reading out more of the transient with ones oscilloscope. In principle one can also extrapolate the transients to areas not measured but with high uncertainty. Error propagation of the results is trivial as one has access to all the errors on the fits. Further the viability of ones model (one versus two exponential fits) can easily be tested by plotting the ratios of the various χ^2 of the fits as a function of temperature as seen in Figure 6. Figure 6 also shows in which areas one-dimensional exponential fits are acceptable.

3. Discussion

Some traps are in reality two traps close together and result in an I-DLTS transient that is a sum of two exponentials. One can fit multiple exponentials to the transients to deconvolute the I-DLTS signal and plot the resulting I-DLTS spectra from each exponential. Deconvolutions are better done at the transient level where one has direct access to the shape

of the transients. In the double boxcar method the transient is processed through a rate window that acts as a smearing function and also limits the amount of information passed about the transient to two points. It is difficult to deconvolute two exponentials from a waveform by sampling it at only two points.

An I-DLTS spectrum from fitting a double exponential to the data are shown in Figure 7 together with the I-DLTS spectrum from each of the exponentials individually. All fits had reasonable chi-squares per degree of freedom. As seen there is a shoulder in the combined double exponential spectrum around $T=90\text{K}$. This shoulder is resolved into two peaks when one looks at the first and second exponential spectrums. Interesting substructure is seen in the $T>175\text{K}$ region and will be explored in future papers. Further around $T=160\text{K}$ where it was not obvious from the combined double exponential that there are two peaks this method picks them out. A blowup of this region is shown in Figure 8. Some peaks are artifacts of the fitting process but can be quickly eliminated them as they are quickly die away at different rate windows and seen to be unphysical.

Note that the traces from the individual exponential fits never go to zero but, for example around $T=200\text{K}$, are actually very close to each other in the position of the peak. There appears to be some spectral leakage between the two exponentials. This probably arises since while there is only one trap, the trap is broad in activation energy and so has exponential slopes close to each other. A more general and precise method is necessary.

In general one should do a Laplace transform of the transient to determine the magnitude and slopes of all the exponential which make up the transient [3,4].

$$f(t) = \int_0^{\infty} F(s) e^{-st} ds$$

The term $F(s)$ in the Laplace transform and gives one the density of the different exponentials that make up the DLTS transient, equivalent to Fourier coefficients which tell one the density of periodic functions which make up a waveform. It is equivalent to fitting an infinite number of exponentials to the data and determining which ones contribute. However, Laplace transforms are notoriously numerically unstable and while various numerical techniques exist in the literature none have been found by us to be stable to noisy data. We feel fitting multiple exponentials to the transient is a particularly simple method to extract the necessary information. One does not know a priori whether two or twenty exponentials are contributing to the transient. Our method involves fitting one, two, three, and four exponentials to the same transient. Then one can compare the chi-squares of the four different fits as seen in Figure 6. When the division of the chi-squares from n and $n+1$ exponentials ($n = \#$ of exponentials) is greater than 1 this indicates than $n+1$ exponentials should be used to characterize the transient. As seen there is no difference between fitting three and four exponentials and indeed the coefficients of the fourth exponential lead to a zero fourth term. In general it appears that fitting three exponentials best characterizes the data and fitting one exponential is not very good. However, two exponential fits are a good first effort at increasing accuracy and deconvolution peaks. While this method can not map the spread in activation energies of broad traps which a Laplace transform would provide it does provide a good deconvolution technique increasing the sensitivity of I-DLTS measurements.

4. Conclusion

A new fast, sensitive, and well-resolved I-DLTS technique has been demonstrated. It increases the resolving power of I-DLTS measurements and is relatively straightforward to implement in systems that use traditional double boxcar systems.

Acknowledgements:

This research was supported by the U.S. Department of Energy: Contract No. DE-AC02-76CH00016.

Reference:

- [1] D.V. Lang, Journal of Applied Physics, Vol. 45, Num. 7, July 1974.
- [2] Z. Li, NIM, A 403, (1998) 399-416.
- [3] L. Dobaczewski et al, Journal of Applied Physics, Vol. 76, Num. 1, July 1994.
- [4] D.D. Nolte et al, Journal of Applied Physics, Vol. 62, Num. 3, August 1987.

Figure 1: The I-DLTS transient with single and double exponential fits. Note that a single exponential fit does not well characterise the transient.

Figure 2: I-DLTS spectrum generated from single and double exponential fits to the I-DLTS transient. Double exponential fits better characterise the transient.

Figure 3: I-DLTS spectrum generated from the double boxcar method and the new multi-exponential fit method. Note that fluctuations in the fit spectrum are smaller. The transients were averaged an identical number of times in both methods.

Figure 4: I-DLTS spectrum generated with one temperature scan with the new method. The Arrhenius curves are clearly visible.

Figure5: Arrhenius plots generated from Figure 4. Also shown are the calculated energies and cross-sections.

Figure 6: By comparing the ratios of chi-squares from fits with different number of exponentials one can evaluate how many exponentials to fit to the DLTS transient in different temperature regions.

Figure 7: I-DLTS spectra should be generated from the two exponentials that make up the double exponential fit. Notice the shoulder at $T=90\text{K}$ is well resolved and a broad peak at $T=160\text{K}$ is deconvoluted.

Figure 8: Detail of Figure 7. Unphysical peaks quickly die away at different rate windows and are easily eliminated.

1
 2
 3
 4
 5
 6
 7
 8
 9
 10
 11
 12
 13
 14
 15
 16
 17
 18
 19
 20
 21
 22
 23
 24
 25
 26
 27
 28
 29
 30
 31
 32
 33
 34
 35
 36
 37
 38
 39
 40
 41
 42
 43
 44
 45
 46
 47
 48
 49
 50
 51
 52
 53
 54
 55
 56
 57
 58
 59
 60
 61
 62
 63
 64
 65
 66
 67
 68
 69
 70
 71
 72
 73
 74
 75
 76
 77
 78
 79
 80
 81
 82
 83
 84
 85
 86
 87
 88
 89
 90
 91
 92
 93
 94
 95
 96
 97
 98
 99
 100
 101
 102
 103
 104
 105
 106
 107
 108
 109
 110
 111
 112
 113
 114
 115
 116
 117
 118
 119
 120
 121
 122
 123
 124
 125
 126
 127
 128
 129
 130
 131
 132
 133
 134
 135
 136
 137
 138
 139
 140
 141
 142
 143
 144
 145
 146
 147
 148
 149
 150
 151
 152
 153
 154
 155
 156
 157
 158
 159
 160
 161
 162
 163
 164
 165
 166
 167
 168
 169
 170
 171
 172
 173
 174
 175
 176
 177
 178
 179
 180
 181
 182
 183
 184
 185
 186
 187
 188
 189
 190
 191
 192
 193
 194
 195
 196
 197
 198
 199
 200
 201
 202
 203
 204
 205
 206
 207
 208
 209
 210
 211
 212
 213
 214
 215
 216
 217
 218
 219
 220
 221
 222
 223
 224
 225
 226
 227
 228
 229
 230
 231
 232
 233
 234
 235
 236
 237
 238
 239
 240
 241
 242
 243
 244
 245
 246
 247
 248
 249
 250
 251
 252
 253
 254
 255
 256
 257
 258
 259
 260
 261
 262
 263
 264
 265
 266
 267
 268
 269
 270
 271
 272
 273
 274
 275
 276
 277
 278
 279
 280
 281
 282
 283
 284
 285
 286
 287
 288
 289
 290
 291
 292
 293
 294
 295
 296
 297
 298
 299
 300
 301
 302
 303
 304
 305
 306
 307
 308
 309
 310
 311
 312
 313
 314
 315
 316
 317
 318
 319
 320
 321
 322
 323
 324
 325
 326
 327
 328
 329
 330
 331
 332
 333
 334
 335
 336
 337
 338
 339
 340
 341
 342
 343
 344
 345
 346
 347
 348
 349
 350
 351
 352
 353
 354
 355
 356
 357
 358
 359
 360
 361
 362
 363
 364
 365
 366
 367
 368
 369
 370
 371
 372
 373
 374
 375
 376
 377
 378
 379
 380
 381
 382
 383
 384
 385
 386
 387
 388
 389
 390
 391
 392
 393
 394
 395
 396
 397
 398
 399
 400
 401
 402
 403
 404
 405
 406
 407
 408
 409
 410
 411
 412
 413
 414
 415
 416
 417
 418
 419
 420
 421
 422
 423
 424
 425
 426
 427
 428
 429
 430
 431
 432
 433
 434
 435
 436
 437
 438
 439
 440
 441
 442
 443
 444
 445
 446
 447
 448
 449
 450
 451
 452
 453
 454
 455
 456
 457
 458
 459
 460
 461
 462
 463
 464
 465
 466
 467
 468
 469
 470
 471
 472
 473
 474
 475
 476
 477
 478
 479
 480
 481
 482
 483
 484
 485
 486
 487
 488
 489
 490
 491
 492
 493
 494
 495
 496
 497
 498
 499
 500
 501
 502
 503
 504
 505
 506
 507
 508
 509
 510
 511
 512
 513
 514
 515
 516
 517
 518
 519
 520
 521
 522
 523
 524
 525

CONF - 980355 - -

199802

DOE/ER, XF

UC - 400, DOE/ER

DOE