AD-A122 902

THE ELECTRICAL AND METALLURGICAL PROPERTIES OF DEFECTS
IN COMPOUND SEMICONDUCTORS(U) STANFORD UNIV CA STANFORD
ELECTRONICS LABS G L PEARSON DEC 82 ARD-12892.5-EL

1/1

UNCLASSIFIED

DAAG29-75-C-0013

P/O 20/13

END
DATE
FILMED
283
DTIC

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ARO 12892.5-EL (12)
15589.3-EL

THE ELECTRICAL AND METALLURGICAL PROPERTIES
OF DEFECTS IN COMPOUND SEMICONDUCTORS

FINAL REPORT

Covering the period 8 February 1975 through 30 September 1982

Prepared under

Army Research Office, Research Triangle Park
Contracts DAAG 29-75-0013
and DAAG 29-78-0018

Approved for Public Release
Distribution Unlimited

DECEMBER 1982

Solid State Electronics Laboratory
Stanford Electronics Laboratories
Stanford University Stanford, California

DTIC
JAN 03 1983
E

AD A122902

DTIC FILE COPY

028

FINAL REPORT

DECEMBER 1982

Approved for Public Release
Distribution Unlimited

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
 526
 527
 528
 529
 530
 531
 532

A

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A122902	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Electrical and Metallurgical Properties of Defects in Compound Semiconductors		5. TYPE OF REPORT & PERIOD COVERED Final Report 8 February 1975 - 30 September 1982
7. AUTHOR(s) Gerald L. Pearson		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford Electronics Laboratory Stanford University Stanford, California 94305		8. CONTRACT OR GRANT NUMBER(s) DAAG 29-75-0013 DAAG 29-78-0018
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE December 1982
		13. NUMBER OF PAGES 11
		15. SECURITY CLASS. (of this report) unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) NA		
18. SUPPLEMENTARY NOTES The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Semiconductor, luminescence, epitaxy, defects, aluminum gallium arsenide		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the research carried out under Contracts DAAG 29-75-0013 and DAAG 29-78-0018. The program on the contract was directed toward the following three separate projects related to the electrical, optical, and metallurgical properties of defects in compound semiconductors: 1. Defects in Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals 2. Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ 3. Properties of Heavily Doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$		

FOREWORD

The studies presented began 8 February 1975 and concluded 30 September 1982. The research activity was conducted under the supervision of Professor Gerald L. Pearson at the Solid State Electronics Laboratory at Stanford University who was also the Principal Investigator.

This is the Final Technical Documentary Report of the work under contracts DAAG 29-75-0013 and DAAG 29-78-0018.

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

THE ELECTRICAL AND METALLURGICAL PROPERTIES OF
DEFECTS IN COMPOUND SEMICONDUCTORS

ABSTRACT

This report summarizes the research carried out under Contracts DAAG 29-C-0013 and DAAG 29-C-0018. The program on the contract was directed toward the following three separate projects related to the electrical, optical, and metallurgical properties of defects in compound semiconductors:

1. Defects in annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals.
2. Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$.
3. Properties of Heavily Doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$.

CHAPTER I

INTRODUCTION

This report summarizes the technical activity at Stanford University under contracts DAAG 29-75-0013 and DAAG 29-78-C-0018 during the period 8 February 1975 to 30 September 1982. The program on this contract was directed toward the following three separate projects related to the electrical, optical, and metallurgical properties of defects in compound semiconductors:

1. Defects in Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals
2. Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$.
3. Properties of Heavily Doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$.

A detailed technical report was prepared for each of the first two projects so that only the abstracts are included in this summary report together with a complete bibliography of all technical papers generated by these projects.

The third project on "Properties of Heavily Doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ " was only partially completed prior to the termination of the contract. It will be continued with alternate financing.

CHAPTER II

Defects in Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals

ABSTRACT

An investigation of the annealing effects in the ternary compound semiconducting system, $\text{Al}_x\text{Ga}_{1-x}\text{As}$, has been carried out. Nondegenerate n-type single crystals always have p-type surface layers after annealing at 800°C for 21 hours in a vacuum. The thickness of this converted p-type surface layer is $\approx 5 \mu\text{m}$ as measured by electron-beam induced current techniques on annealed boat-grown (n)GaAs crystals having an electron concentration of $\approx 3 \times 10^{16} \text{ cm}^{-3}$. Capacitance-voltage measurements on the anneal-induced p-n junction shows that it is linearly graded.

Photoluminescent measurements were employed to study the radiative defects in the converted surface layers. Photoluminescent bands due to shallow acceptors such as Si_{As} and $\text{Si}_{\text{As}}-\text{V}_{\text{As}}$ were detected in annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ single crystals. An oxygen level at 0.71 eV was also detected in annealed GaAs but not in as-grown samples. Besides the bands due to shallow acceptors, broad deep level emission bands were also observed in annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$. Sn_{As} deep acceptors were detected in annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Sn}$ and $\text{V}_{\text{Ga}}-\text{Te}$ (or $\text{V}_{\text{Al}}-\text{Te}$) complexes in annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Te}$. Two prominent bands located at 1.53 and 1.46 eV, independent of Al composition x , were detected in as-grown (p) $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Ge}$. The 1.53 eV band is thought to arise from $\text{V}_{\text{Ga}}-\text{Ge}_{\text{As}}$ complexes. The other has not been identified. $\text{V}_{\text{As}}-\text{Ge}_{\text{As}}$ complexes were also introduced into $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Ge}$ during heat treatment.

Transient capacitance techniques were used to study nonradiative defects in as-grown and annealed samples. Two electron traps were found in as-grown $(n)Al_xGa_{1-x}As:Sn$ single crystals when x was greater than 0.2. One is located 0.08 eV below the conduction band and the ionization energy of the other varies from 0.15 to 0.19 eV as x increases from 0.21 to 0.35. It is noted that these electron traps are present in the same range of Al composition where the electron activation energy in $(n)Al_xGa_{1-x}As:Sn$, as obtained from Hall measurements, increases sharply with respect to x . It is believed that this increase in the electron activation energy with respect to x is caused by the presence of these two electron traps.

A hole trap, introduced by annealing, was found in $(p)Al_xGa_{1-x}As:Ge$. This level is located 0.42 eV above the top of the valence band and is independent of x . Arguments are given to show that this trap is due to Ga (or Al) vacancies rather than Cu impurities as reported in the literature. A model is presented to support the view that Ga vacancies are hole traps and As vacancies electron traps.

The above abstract is from the Ph.D. thesis of Kou-I Chang as given in Report SU-SEL-78-019, Stanford Electronics Laboratories, Stanford, California, June 1978. One technical paper [1] and one oral presentation [2] originated from this work. Dr. Chang is now employed at Hewlett Packard Company, Palo Alto, California.

10201

CHAPTER III

Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$

ABSTRACT

The electronic transport properties of holes in p-type $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$ are systematically investigated. Detailed studies are made of the carrier concentrations, carrier mobilities, impurity activation energy and impurity distribution coefficients.

Single crystal layers of $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$ have been grown throughout the composition range $0.0 < x < 1.0$ on (100) semi-insulating GaAs:Cr substrates using liquid phase epitaxial techniques. The Al distribution coefficient and growth rate at 800°C are investigated. Carrier concentrations, Hall mobilities and resistivities are measured as a function of temperature from 77 to 300K.

A transport model based upon the relaxation time approach is used to calculate the hole mobility in the degenerate heavy and light hole valence bands of $\text{Al}_x\text{Ga}_{1-x}\text{As}$. All of the major scattering mechanisms are included in the calculations.

The temperature variation of the hole mobilities are analyzed using theoretical models to determine the relative contributions of each of the scattering processes to the total mobility. Excellent agreement between calculated and experimental mobilities is obtained by considering acoustic deformation potential, piezoelectric, nonpolar optical, polar optical and ionized impurity scattering. The scattering potentials for acoustic deformation potential and nonpolar optical scattering

are determined as $E_{DP} = 5.25$ eV and $E_{NP} = 10.65$ eV in GaAs and as $E_{DP} = 6.84$ eV and $E_{NP} = 13.65$ eV in AlAs. The major scattering processes which limit the mobility of holes in pure $Al_xGa_{1-x}As$ are the deformation potential, nonpolar optical and polar optical interactions. The piezoelectric and alloy scattering interactions have a minor effect on the mobility. The lattice mobility of holes in pure $Al_xGa_{1-x}As$ follows a $T^{-2.3}$ temperature dependence at all Al compositions. The lattice mobility decreases from 400 $cm^2/V\text{-sec}$ in GaAs to 120 $cm^2/V\text{-sec}$ in AlAs.

The incorporation of Ge as an amphoteric impurity in $Al_xGa_{1-x}As$ is investigated. The Ge activation energy increases with Al composition as $E_A(x) = 10 + 175x$ meV. The total acceptor concentrations, donor concentrations and degree of compensation in the $Al_xGa_{1-x}As:Ge$ crystals are determined. The distribution coefficient of Ge at both acceptor sites and donor sites decreases exponentially with increasing Al composition. The $Al_xGa_{1-x}As:Ge$ crystals become closely compensated with increasing Al composition. The acceptor to donor concentration ratio is $N_A/N_D = 2.7$ in GaAs and decreases to $N_A/N_D \sim 1$ in AlAs.

The above abstract is from the Ph.D. thesis of Kevin Gene Wah Jew, Stanford Electronics Laboratories, Stanford, California, March 1982. One technical paper [3] originated from this work and a second [4] is in preparation. Dr. Jew is now employed at Philips Research Laboratories, Sunnyvale, California.

CHAPTER IV

Properties of Heavily Doped AlGaAs

ABSTRACT

Work this year has involved further characterization of heavily doped AlGaAs. Of particular interest has been determination of the mechanisms involved in the photoluminescence spectra observed in both degenerate n type AlGaAs:Te and degenerate p-type AlGaAs:Ge. In AlGaAs:Te with low Al compositions, above band gap luminescence is observed. This has been attributed to a Burstein-Moss type shift involving very little distortion of the conduction band. Attempts are under way to correlate the peak position with electron density and the peak shape with the joint density of states. Also observed in AlGaAs:Te is a previously unreported infrared peak at 0.95 eV. This peak, which occurs for all levels of Te doping, may be due to a Ga-Te complex.

In AlGaAs:Ge, significant distortion of the valence band is believed to occur. The large hole effective mass prevents screening of the acceptor impurity levels and thus permits the formation of band edge tails and impurity bands. Therefore the peak luminescence energy occurs at an energy lower than the intrinsic band gap. Models are being developed to explain both the peak position and peak width as a function of hole concentration for various Al compositions.

Finally an anomalous peak is observed in structures consisting of heavily doped epitaxial layers grown on GaAs:Cr substrates. While other investigators have attributed a luminescence peak at 1.43 eV to

the substrate, our studies show that if this peak originates from the substrate, it is induced by the epitaxial layer. Samples with epitaxial layers thinner than 0.5 μm show no evidence of this peak, while in samples with thicker epitaxial layer, this peak can predominate. Its asymmetric shape and the properties already mentioned make this characterization a prime goal of future work.

The above abstract describes the research project of Kevin Malloy. He expects to complete this work and meet all requirements for the Ph.D. degree in August 1983. Mr. Malloy is in the ROTC program and will report for active duty at the Wright-Patterson Air Force Base after receiving his degree.

REFERENCES

1. "Defects in As-Grown and Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals", K. I. Chang and G. L. Pearson, J. of Luminescence 20, 131 (1979).
2. "Photoluminescence Studies of Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals", K. I. Chang and G. L. Pearson, Bull. Am. Phys. Soc. 23, 17 (1978).
3. "Effect of GaAs or $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Oxide Composition on Schottky Barrier Behavior", C. M. Garner, C. Y. Su, W. A. Saperstein, K. G. Jew, C. S. Lee, G. L. Pearson and W. E. Spicer, J. Appl. Phys. 50, 3376 (1979).
4. "Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ", K. G. W. Jew and G. L. Pearson, Paper in preparation.

DATE
ILME

carrier concentrations, carrier mobilities, impurity activation energy and impurity distribution coefficients.

Single crystal layers of $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$ have been grown throughout the composition range $0.0 < x < 1.0$ on (100) semi-insulating GaAs:Cr substrates using liquid phase epitaxial techniques. The Al distribution coefficient and growth rate at 800°C are investigated. Carrier concentrations, Hall mobilities and resistivities are measured as a function of temperature from 77 to 300K.

A transport model based upon the relaxation time approach is used to calculate the hole mobility in the degenerate heavy and light hole valence bands of $\text{Al}_x\text{Ga}_{1-x}\text{As}$. All of the major scattering mechanisms are included in the calculations.

The temperature variation of the hole mobilities are analyzed using theoretical models to determine the relative contributions of each of the scattering processes to the total mobility. Excellent agreement between calculated and experimental mobilities is obtained by considering acoustic deformation potential, piezoelectric, nonpolar optical, polar optical and ionized impurity scattering. The scattering potentials for acoustic deformation potential and nonpolar optical scattering

$T^{-2.3}$ temperature dependence at all Al compositions. The lattice mobility decreases from $400 \text{ cm}^2/\text{V-sec}$ in GaAs to $120 \text{ cm}^2/\text{V-sec}$ in AlAs.

The incorporation of Ge as an amphoteric impurity in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is investigated. The Ge activation energy increases with Al composition as $E_A(x) = 10 + 175x \text{ meV}$. The total acceptor concentrations, donor concentrations and degree of compensation in the $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$ crystals are determined. The distribution coefficient of Ge at both acceptor sites and donor sites decreases exponentially with increasing Al composition. The $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$ crystals become closely compensated with increasing Al composition. The acceptor to donor concentration ratio is $N_A/N_D = 2.7$ in GaAs and decreases to $N_A/N_D \sim 1$ in AlAs.

The above abstract is from the Ph.D. thesis of Kevin Gene Wah Jew, Stanford Electronics Laboratories, Stanford, California, March 1982. One technical paper [3] originated from this work and a second [4] is in preparation. Dr. Jew is now employed at Philips Research Laboratories, Sunnyvale, California.

degenerate n type AlGaAs:Te and degenerate p-type AlGaAs:Ge. In AlGaAs:Te with low Al compositions, above band gap luminescence is observed. This has been attributed to a Burstein-Moss type shift involving very little distortion of the conduction band. Attempts are under way to correlate the peak position with electron density and the peak shape with the joint density of states. Also observed in AlGaAs:Te is a previously unreported infrared peak at 0.95 eV. This peak, which occurs for all levels of Te doping, may be due to a Ga-Te complex.

In AlGaAs:Ge, significant distortion of the valence band is believed to occur. The large hole effective mass prevents screening of the acceptor impurity levels and thus permits the formation of band edge tails and impurity bands. Therefore the peak luminescence energy occurs at an energy lower than the intrinsic band gap. Models are being developed to explain both the peak position and peak width as a function of hole concentration for various Al compositions.

Finally an anomalous peak is observed in structures consisting of heavily doped epitaxial layers grown on GaAs:Cr substrates. While other investigators have attributed a luminescence peak at 1.43 eV to