Appendix A

THERMAL MODEL FOR THE SIMPLE MICROBOLOMETER

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*
*      This program handles both the steady state 'dc' case and the time dependent
*      case of a 2 dimensional body.  It is written in Fortran 77, to be run
*      on a Macintosh Plus computer.
*      The problem is symmetrical, so will only do half, treating the
*      cut portion as a perfect insulator.
*
*      The method of solving the problem is a finite-difference approach
*      where thermal resistance elements are used in a Gauss-Seidel
*      iteration.(see J.P.Holman,Heat Transfer,4th ed.,eqn.4-43(page130).
*
*      NOTE: in this program, column 1 is considered an insulating wall
*            and column = (COL) is a thermal sink.  Row 1 is a perfect
*            insulator (it is a layer of air above the device), and
*            row = (ROW) is a thermal sink. The antenna is also a sink.

*******      DEFINITION OF TERMS      ******************
*
*      Detector
*      alpha              (dR/RdT) in 1/°K
*      CIdet              heat capacity (µW-sec/°K) of element
*      kdet               thermal conductivity in W/(cm-°K)
*      Ldet               lengths (µm) of the films studied
*      rhodet             density (g/cm**3)
*      Rodet              elect resistance at 300K for 1 element
*      SHdet              specific heat, (cal/(gm-°K)
*      sigdet             electical conductivity in 1/(Ω-cm)
*      detthk             film thickness in Å
*
*      Substrate
*      CIsub              heat capacity (µW/(K-sec)) of element
*      ksub               thermal conductivity in W/(cm-°K)
*      Lsub               length(µm) of the substrate considered
*      rhosub       density (g/cm**3)
*      SHsub        specific heat, (cal/(gm-°K)
*      subth              thickness of each row in top,bot(Å)
*
*      OPERATING PARAMETERS
*      Ibias              bias current in mA
*      Irf                radiation current, modulated by sin(wt)
*      maxdev             the max Tdev for one iteration
*      SumRe        1/2 the total bolometer resistance (Ω)
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*       Tamb                ambient temperature °K
*       Tdev                deviation in T(old) with T(new)
*       R0                  detector resistance (Ω) with no Irf
*       R1                  detector resistance (Ω) at Irf#1
*       Resp                responsivity (V/W)
*       flaga               indicates uniform det. thickness, or not
*
*       ELEMENT PARAMETERS
*       delx,dely           the finite increments used, in µm
*       DE                  the time increment,(sec)
*       DEV                 the allowed Temp deviation to quit iterating
*       COL                 the total number of increments (columns)
*       fname               filename for output
*       ROW                 total number of layers deep
*       N                   the number of increments in the Bi
*       Q(X)                heat generated by I**2*R, in µW
*       thicktc(X)          thickness of Xth detector element
*       Zx(X,Z)             thermal R(°K/µW) in x dir of Mth element
*       Zz(X,Z)             thermal R(°K/µW) in z dir of Mth element
*       RE(X)           the electical R(Ω) of the Mth element
*       CI(X,Z)             heat capacity of an (x,z) element
*       Tm(X,Z)             temperature (°K) of (X,Z)th element
*       X,Z,K,user          misc. counters
*       TOP,BOT             variables to hold GSITER intermed. values
*       ORD                 max dimension size
*       Ttop                temperary temperature vaiable
*       Ts(X,Z)             temporary temp array
*       Tp(X,Z)             element temp, steady state, and present time
*       TLO,TT,THI          used in iterative routine for isotherm
*       ZRLO,ZRT,ZRHI       ditto
*       XPOS,ZPOS
*       T

* note: the CI and Ts arrays are not used in the steady state analysis.

****          DEFINE VARIABLE TYPES ***************

        Integer ORD,REP
        PARAMETER (ORD = 30)
        PARAMETER (REP = 8)

*       VARIABLES
*       For det
        Real*8          alpha,CIdet,kdet,Ldet,rhodet,Rodet,SHdet
        Real*8          sigdet,detthk,R0,R1,thkdet
*       For Substrate
        Real*8          CIsub,ksub,Lsub,rhosub,SHsub
```

```
      Real*8              topsubth,botsubth
      Integer             topsub,botsub
*     For OPERATING PARAMETERS
      Real*8        Ibias,Irf,maxdev,Tamb,Tdev
      Real*8        Resp,SumRe,TOP,BOT
      Integer       COL,ROW
      Character     isofname*20,flaga*10

*     FOR ELEMENT PARAMETERS
      Real*8        delx,dely,DEV,ruser
      Real*8        Xpos,Zpos,T,PI
      Integer       M,N,X,Z,K,user,I,JJ,PRG

*     TIME DEPENDENT STUFF
      Real*8        th,time,rfI,V,ntime,W,Vpp
      Real*8        Vmax,Vmin,Rmax,Rmin,f,DE,totime
      Integer       DELAY,DUR,tinc

* initialize arrays
      Real*8        Zx(ORD,ORD),Zz(ORD,ORD)
      Real*8        ZP(ORD),ISO(ORD,ORD),XP(ORD)
      Real*8        CI(ORD,ORD),Tp(ORD,ORD)
      Real*8        Q(ORD),thickdet(ORD),RE(ORD)
      Real*8        ZD(ORD,ORD),Tm(ORD,ORD)
      Real*8        TV(3,1000)

*****         SET DEFAULT VALUES      **********
*     Detector:
            alpha = -.003
            kdet = 0.040
            Ldet = 2.0
            rhodet = 9.80
            SHdet = 0.30
            sigdet = 1100.
            detthk = 1000.0

*     Substrate:
            ksub = 0.008
            rhosub = 2.2
            SHsub = 0.180
            subth = 2500.0
            Lsub = 4.0

*     OPERATING PARAMETERS:
            Ibias = 1.0
            Irf = 0.0100
            Tamb = 300.0
            PI = 3.1415926536
```

```
            isofname = 'tdmb.dat'
            flaga = 'row'

*       ELEMENT PARAMETERS:
            DEV = 1.0E-06
            COL = 12
            ROW = 13
            dely = 3.5

*       TIME DEPENDENT STUFF:
            time = 0.0
            Vmax = 0.
            Vmin = 1.d9
            Rmax = 0.
            Rmin = 1.d9
            DELAY = 2
            DUR = 1
            f = 3.d5
            DE = 25.d9
            PRG = 0

*****       PROMPT USER FOR NEW DEFAULT VALUES   *****
5       Write(9,*) 'enter one of the following:'
        Write(9,*) 'change physical parameters               [0]'
        WRITE(9,*) 'execute the steady state program         [1]'
        WRITE(9,*) 'execute the time dependent program       [2]'
        WRITE(9,*) 'exit the program                         [3]'
        Read(9,*) user
        GO TO (10,100,105,600),user + 1
        GO TO 5

10      Write(9,*) 'change:    detector:          [0]'
        Write(9,*) '           substrate:         [1]'
        Write(9,*) '           elements/misc: [2]'
        Write(9,*) '           frequency:         [3]'
        Write(9,*) 'go to starting menu           [4]'
        Read(9,*) user
        GO TO (15,20,25,30,5),user + 1
        GO TO 10

***     Change detector parameters
15      Write(9,*) 'DETECTOR:'
        Write(9,*) '     TCR (1/K) = ',alpha
        Read(9,*) alpha
        Write(9,*) '     thermal conductivity (W/(cm-K))',kdet
        Read(9,*) kdet
        Write(9,*) 'length in μm',Ldet
        Read(9,*) Ldet
```

```
      Write(9,*) 'Density (g/cm**3)',rhodet
      Read(9,*) rhodet
      Write(9,*) 'specific heat (cal/(g-K))',SHdet
      Read(9,*) SHdet
      Write(9,*) 'electrical conductivity (1/Ω-cm)',sigdet
      Read(9,*) sigdet
      Write(9,*) 'film thickness (Å)',detthk
      Read(9,*) detthk
      GO TO 10

***   Change substrate parameters
20    Write(9,*) 'SUBSTRATE:'
      Write(9,*) '     thermal conductivity (W/(cm-K))',ksub
      Read(9,*) ksub
      Write(9,*) 'length in μm',Lsub
      Read(9,*) Lsub
      Write(9,*) 'Density (g/cm**3)',rhosub
      Read(9,*) rhosub
      Write(9,*) 'specific heat (cal/(g-K))',SHsub
      Read(9,*) SHsub
      Write(9,*) 'substrate layer row thickness:',subth
      Read(9,*) subth
      GO TO 10

***   Change element/misc parameters
25    Write(9,*) 'ELEMENTS and MISC:'
      Write(9,*) 'number of columns:',COL
      Read(9,*) COL
      Write(9,*) 'number of rows:',ROW
      Read(9,*) ROW
      Write(9,*) 'allowed temp deviation:',DEV
      Read(9,*) DEV
      Write(9,*) 'delta Y:',dely
      Read(9,*) dely
      Write(9,*) 'Bias current (mA):',Ibias
      Read(9,*) Ibias
      Write(9,*) 'rf current (mA):',Irf
      Read(9,*) Irf
      Write(9,*) 'ambient temperature (K):',Tamb
      Read(9,*) Tamb
      Write(9,*) 'filename for isothermal plot: ',isofname
      Read(9,*) isofname
      GO TO 10

****  change frequency
30    Write(9,*) 'enter modulation frequency:',f
      Read(9,*) f
      delx = Lsub/(COL - 2)
```

```
      DE = 625.d-9 * delx**2
      tinc = INT(1./(f*DE))
      Write(9,*) 'recommend ',tinc,' points/cycle'
      Write(9,*) 'enter # points/cycle:',tinc
      Read(9,*) tinc
      DE = 1./(f*tinc)
      Write(9,*) 'delay before taking data (cycles):',DELAY
      Read(9,*) DELAY
      GO TO 10

*****         intitialize arrays        **********
***   calculate element values
100   PRG = 1
      GO TO 110
105   PRG = 2
110   delx = Lsub/(COL - 2)
      N = Int(Ldet/delx)
      CIdet = rhodet * SHdet * delx * dely * 4.184D-10
      CIsub = rhosub*SHsub* delx * dely * 4.184D-10
      Rodet = (delx * 1.0D+8)/(sigdet*dely*detthk)

***   set parameters for insulating walls
*     (at col=1 and at row=1)
      X = 1
      do 115 Z=2,ROW-1
            Zx(X,Z) = 1.D12
            Zz(X,Z) = 1.D12
115   continue
      Z = 1
      do 120 X=1,COL
            Zx(X,Z) = 1.D12
            Zz(X,Z) = 1.D12
120   continue

***   set parameters for thermal sinks
*     (at col=COL,row=ROW, and antenna region
*           where col=N+2 to COL-1)
      X = COL
      do 125 Z=2,ROW-1
            Zx(X,Z) = 0.
            Zz(X,Z) = 0.
125   continue
      Z = ROW
      do 130 X=1,COL
            Zx(X,Z) = 0.
            Zz(X,Z) = 0.
130   continue
      Z = 2
```

```
      do 135 X=N+2,COL-1
            Zx(X,Z) = 0.
            Zz(X,Z) = 0.
135   continue

***   set parameters for the detector
      do 140 X=2,N+1
            Zx(X,2) = (delx*100.0)/(kdet*dely*detthk)
            Zz(X,2) = detthk/(dely*delx*kdet*1.D6)
            CI(X,2) = CIdet*detthk
            RE(X)= Rodet
140   continue

***   set parameters for the substrate
      do 150 Z=3,ROW-1
            do 145 X=2,COL-1
            Zx(X,Z) = (delx*100.0)/(ksub*dely*subth)
            Zz(X,Z) = subth/(dely*delx*ksub*1.D6)
            CI(X,Z) = CIsub*subth
145         continue
150   continue

***   initialize arrays
      do 160 X=1,COL
            Q(X) = 0.
            do 155 Z=1,ROW
                  Tm(X,Z) = Tamb
                  Tp(X,Z) = Tamb
                  ZD(X,Z)= 0.
155         continue
160   continue

*****       FIND STEADY STATE T(X,Z)        **********
      Write(9,*) 'starting steady state routine'
*     determine heat generation terms
      K = 0
200   maxdev = 0.
      K = K+1
      do 205 X=2,N+1
            Q(X) = (Ibias**2)*RE(X)
205   continue

      CALL GSITER(ROW,COL,Tm,Zx,Zz,ZD,ZD,DE,Q,TOP,BOT,N,
   +        Tdev,maxdev,ORD)

***   calculate new RE(I)
      do 210 I=2,N+1
      RE(I)=Rodet*((alpha*(Tm(I,2)-Tamb))+1.)
```

```
210     continue

        IF(maxdev .gt. DEV) go to 200
        SumRe = 0.0
        Do 215 X=2,N+1
                SumRe = SumRe + RE(X)
215     continue
        R0 = SumRe
        Write(9,*) 'end of steady state. # iter= ',K
        Write(9,*) 'steady state full R = ',2.*R0
        IF(PRG.eq.2) go to 400

        K = 0
220     maxdev = 0.
        K = K+1
        do 225 X=2,N+1
                Q(X) = (Ibias**2 + PI*(Irf**2))*RE(X)
225     continue

        CALL GSITER(ROW,COL,Tm,Zx,Zz,ZD,ZD,DE,Q,TOP,BOT,N,
   +            Tdev,maxdev,ORD)

***     calculate new RE(I)
        do 230 I=2,N+1
        RE(I)=Rodet*((alpha*(Tm(I,2)-Tamb))+1.)
230     continue

        IF(maxdev .gt. DEV) go to 220
        Write(9,*) 'end of 2nd steady state. # iter= ',K
                SumRe = 0.0

        Do 235 X=2,N+1
                SumRe = SumRe + RE(X)
235     continue
        R1 = SumRe
        Resp = 2000.*(Ibias*(R1-R0))/(PI*Irf**2*(R0+R1))
        Write(9,*) 'for Irf= ',Irf,' Resp = ',Resp
        Write(9,*) 'biased full R = ',2.*R1
        Write(9,*) char(7)

240     Write(9,*) '[0]=new run,[1]=isotherm,[2]=stop'
        Read(9,*) user
        GO TO (5,245,600),user + 1

*****           ISOTHERM ROUTINE          **********
245     Write(9,*) 'isotherm'
*       first put Xpos and Zpos into arrays
        Do 255 X=2, COL-1
```

```
            Z = 2
            Xpos = (X-1.5) * delx
            XP(X) = Xpos
            Zpos = .5*td
            ZP(Z) = Zpos
            Do 250 Z=3,ROW - 1
            Zpos = td + (Z-2.5)*ts
            ZP(Z) = Zpos
250         continue
255     continue

*       find max T
        THI=Tamb
        do 265 X=2,COL-1
        do 260 Z=2,ROW-1
        TS = Tm(X,Z)
        IF(TS.GT.THI) THEN
        THI=TS
        END IF
260     continue
265     continue
        write(9,*) 'peak element temp (K) = ',THI

*       now run find isotherms
        Write(9,*) ' enter the target temperature: ',TT
        Read(9,*) TT
        Write(9,*) 'filename?'
        Read(9,*) isofname

* initialize ISO array
        do 275 X=2,COL-1
        do 270 Z=1,6
        ISO(X,Z) = 0.
270     continue
275     continue

        do 305 X=2,COL-1
        M = 1
        Z = 2
        TS = Tm(X,Z)
        IF(TS.GT.TT) THEN
        GO TO 290
        END IF
        TLO = TS
        ZRLO = ZP(Z)
280     Z = Z+1
        IF (Z.EQ.ROW) THEN
        GO TO 305
```

```
        END IF
        TS = Tm(X,Z)
        IF(TS.GT.TT) THEN
        GO TO 285
        END IF
        IF(TS.GT.TLO) THEN
                TLO = TS
                ZRLO = ZP(Z)
        END IF
        GO TO 280
285     THI = TS
        ZRHI = ZP(Z)
        CALL INTERP(TLO,TT,THI,ZRLO,ZRT,ZRHI)
        ISO(X,M) = ZRT
        M=M+1
290     THI = TS
        ZRHI = ZP(Z)
295     Z = Z+1
        IF (Z.EQ.ROW) THEN
        GO TO 305
        END IF
        TS = Tm(X,Z)
        IF(TS.LT.TT) THEN
        GO TO 300
        END IF
        IF(TS.LT.THI) THEN
                THI = TS
                ZRHI = ZP(Z)
        END IF
        GO TO 295
300     TLO = TS
        ZRLO = ZP(Z)
        CALL INTERP(TLO,TT,THI,ZRLO,ZRT,ZRHI)
        ISO(X,M) = ZRT
        M=M+1
        GO TO 280
305     CONTINUE

*       OUTPUT ISOTHERM DATA TO TEXT FILE
310     OPEN(UNIT=12,FILE=isofname)
        DO 320 X=2,COL-1
        Xpos = XP(X)
        Z1 = ISO(X,1)
        Z2 = ISO(X,2)
        Z3 = ISO(X,3)
        Z4 = ISO(X,4)
        Z5 = ISO(X,5)
        Z6 = ISO(X,6)
```

```
      WRITE(12,315) Xpos,CHAR(9),Z1,CHAR(9),Z2,CHAR(9),
    + Z3,CHAR(9),Z4,CHAR(9),Z5,CHAR(9),Z6
315   FORMAT(1X,E12.6,a1,E12.6,a1,E12.6,a1,E12.6,a1,
    + E12.6,a1,E12.6,a1,E8.4)
320   continue
      CLOSE(UNIT=12)
      GO TO 240

*****         TIME DEPENDENT ROUTINE         **********
400   time = 0.0
      DE = 1/(f*16.)
      user = DELAY*16 -1
      do 425 I=1,user

      do 405 JJ=1,REP
      CALL GSITER(ROW,COL,Tp,Zx,Zz,CI,Tm,DE,Q,TOP,BOT,N,
    +         Tdev,maxdev,ORD)
405   continue
      do 415 X=1,COL
              do 410 Z=1,ROW
              Tm(X,Z) = Tp(X,Z)
410           continue
415   continue
      th = 2*PI*f*time + PI/2.
      A = PI*.250*((cos(th))**2 + 2*cos(th) + 1.)

***   calculate new RE(I)
      do 420 X=2,N+1
      RE(X)=Rodet*((alpha*(Tm(X,2)-Tamb))+1.)
      Q(X) = (Ibias**2 + A*Irf**2) * RE(X)
420   continue
      time = time + DE
      Write (9,*) I,' of ',user
425   continue

***   run time dependent loop
***   start loop; run 1 cycle before taking data
      time = 0.0
      DE = 1./(f*tinc)
      do 450 I=1,tinc
              do 430 JJ=1,REP
      CALL GSITER(ROW,COL,Tp,Zx,Zz,CI,Tm,DE,Q,TOP,BOT,N,
    +         Tdev,maxdev,ORD)
430   continue
      do 440 X=1,COL
              do 435 Z=1,ROW
              Tm(X,Z) = Tp(X,Z)
435           continue
```

```
440     continue
        th = 2*PI*f*time + PI/2.
        A = PI*.250*((cos(th))**2 + 2*cos(th) + 1.)

***     calculate new RE(I)
        do 445 X=2,N+1
        RE(X)=Rodet*((alpha*(Tm(X,2)-Tamb))+1.)
        Q(X) = (Ibias**2 + A*Irf**2) * RE(X)
445     continue
        time = time + DE
        Write (9,*) I,' of ',tinc
450     continue

*** start taking data
        time = 0.0
        totime = DUR*tinc
        do 480 I=1,DUR*tinc

        do 455 JJ=1,REP
        CALL GSITER(ROW,COL,Tp,Zx,Zz,CI,Tm,DE,Q,TOP,BOT,N,
    +           Tdev,maxdev,ORD)
455     continue
        do 465 X=1,COL
                do 460 Z=1,ROW
                Tm(X,Z) = Tp(X,Z)
460             continue
465     continue
        th = 2*PI*f*time + PI/2.
        A = PI*.250*((cos(th))**2 + 2*cos(th) + 1.)
        rfI = 0.5*(cos(th) + 1.) * Irf

***     calculate new RE(I)
        do 470 X=2,N+1
        RE(X)=Rodet*((alpha*(Tm(X,2)-Tamb))+1.)
        Q(X) = (Ibias**2 + A*Irf**2) * RE(X)
470     continue
        time = time + DE
        SumRe = 0.0
        do 475 X=2,N+1
                SumRe = SumRe + RE(X)
475     continue

        V=Ibias * SumRe * 2000.
***     note: this V is in μV, for a full length bol
        ntime = time/DE
        TV(1,I) = ntime
        TV(2,I) = V
        TV(3,I) = rfI
```

```
      IF(V.gt.Vmax) THEN
            Vmax = V
            Rmax = 2*SumRe
            END IF
      IF(V.lt.Vmin) THEN
            Vmin = V
            Rmin = 2 * SumRe
            END IF
      Write(9,*) ntime,char(9),totime,char(9),SumRe,char(9),V
480   continue

      W = PI*Irf**2*(Rmax+Rmin)/2.
      Vpp = Vmax-Vmin
      Resp = Vpp/W
      Write(9,*) '     f        Vpp       W        Resp'
      Write(9,*) f,char(9),Vpp,char(9),W,char(9),Resp

***   print out ntime,V and rfI
      OPEN(UNIT=12,FILE=isofname)
      Do 490 I=1,DUR*tinc
      ntime = TV(1,I)
      V = TV(2,I)
      rfI = TV(3,I)
      Write(12,485) ntime,char(9),V,char(9),rfI
485   Format(1x,E12.6,a1,E22.16,a1,E22.16)
490   continue
      CLOSE(UNIT=12)
      Vmax = 0.
      Vmin = 1.D9
      Write(9,*) char(7)

495   Write(9,*) '[0]=new run,[1]=stop'
      Read(9,*) user
      GO TO (5,600),user + 1

600   pause 'return to stop'
605   stop
      end

******************************************************************
      SUBROUTINE INTERP(TLO,TT,THI,ZRLO,ZRT,ZRHI)
      Real*8 TLO,TT,THI,ZRLO,ZRT,ZRHI

      If((THI-TLO).eq.0.) then
      ZRT = ZRLO
      Else
      ZRT = ZRLO + ((TT-TLO)/(THI-TLO))*(ZRHI-ZRLO)
      End If
```

```
      RETURN
      END

*****************************************************************
      SUBROUTINE GSITER(ROW,COL,Tp,Zx,Zz,CI,Tm,DE,
   +        Q,TOP,BOT,N,Tdev,maxdev,ORD)
      INTEGER ROW,COL,X,Z,ORD,N
      Real*8 Zx(ORD,ORD),Zz(ORD,ORD),
   +        CI(ORD,ORD),Tp(ORD,ORD),Q(ORD),
   +        Tm(ORD,ORD),Tdev,maxdev,TOP,BOT,DE

      Z = 2
      DO 10 X=2,N+1

      TOP = Q(X) + 2.*Tp(X-1,Z)/(Zx(X,Z)+Zx(X-1,Z)) +
   +        2.*Tp(X+1,Z)/(Zx(X,Z)+Zx(X+1,Z)) +
   +        2.*Tp(X,Z-1)/(Zz(X,Z)+Zz(X,Z-1)) +
   +        2.*Tp(X,Z+1)/(Zz(X,Z)+Zz(X,Z+1)) +
   +        CI(X,Z)*Tm(X,Z)/DE
      BOT = 2./(Zx(X,Z)+Zx(X-1,Z)) +
   +        2./(Zx(X,Z)+Zx(X+1,Z)) +
   +        2./(Zz(X,Z)+Zz(X,Z-1)) +
   +        2./(Zz(X,Z)+Zz(X,Z+1)) + CI(X,Z)/DE
      Tdev = TOP/BOT - Tp(X,Z)
      Tdev = ABS(Tdev)
      Tp(X,Z) = TOP/BOT
      IF (maxdev .gt. Tdev) go to 10
      maxdev = Tdev
10    continue

      DO 40 X=2,COL-1
      DO 30 Z=3,ROW-1

      TOP = 2.*Tp(X-1,Z)/(Zx(X,Z)+Zx(X-1,Z)) +
   +        2.*Tp(X+1,Z)/(Zx(X,Z)+Zx(X+1,Z)) +
   +        2.*Tp(X,Z-1)/(Zz(X,Z)+Zz(X,Z-1)) +
   +        2.*Tp(X,Z+1)/(Zz(X,Z)+Zz(X,Z+1)) +
   +        CI(X,Z)*Tm(X,Z)/DE
      BOT = 2./(Zx(X,Z)+Zx(X-1,Z)) +
   +        2./(Zx(X,Z)+Zx(X+1,Z)) +
   +        2./(Zz(X,Z)+Zz(X,Z-1)) +
   +        2./(Zz(X,Z)+Zz(X,Z+1)) + CI(X,Z)/DE
      Tdev = TOP/BOT - Tp(X,Z)
      Tdev = ABS(Tdev)
      Tp(X,Z) = TOP/BOT
      IF (maxdev .gt. Tdev) go to 30
      maxdev = Tdev
30    continue
```

```
40      continue
        RETURN
        END
```

Appendix B
ROUTINE PHOTOLITHOGRAPHY

1. Pre-clean
    a. Clean slides in acetone, ethanol, high purity water (HPH_2O). Bake dry.
    b. Full power O_2 plasma, 5 minutes. (O_2 at 600 mtorr, glass chamber; precede with a 5 minute O_2 flush).
    c. Rinse in HPH_2O.
    d. Dry at 125°C for at least 15 minutes.

2. Spin-on primer and photoresist
    a. Apply adhesion promoter.
        • apply enough to thoroughly cover chip
        • let stand 10 seconds before spinning
        • spin at 4000 rpm for 30 seconds
    b. Apply 1350J-SF photoresist (4000 rpm, 30 sec).

3. Pre-bake
    a. Bake for 25 minutes at 85°C.

4. Expose
    a. Expose for 85 sec through mask.
        • at radiation power of 2.5 mW/cm^2 incident on top of mask.

5. Develop
    a. Develop in Shipley 452 developer for 60 sec; gentle agitation. Double dip-rinse in HPH_2O.
    b. Blow dry.

6. Flood expose
    a. Expose entire chip for 85 seconds.

7. Postbake
    a. Bake at 125°C for 10 minutes.

Note: I usually skip the flood exposure step.

Appendix C
ELECTROPLATING

This procedure has been used to electroplate gold contacts to chips and printed circuit boards. The procedure was initially outlined in High Frequency Characteristics of Tape Automated Bonding (S.M. Wentworth, Masters Thesis, The University of Texas at Austin, 1987) as a method for electroplating gold bumps on a test chip.

1. Set up the electroplating apparatus as shown in Fig. A.1.
    - since the plating solution evolves cyanide gas, apparatus must be set up in a properly ventilated hood.
2. Warm the electroplate solution to 55-60 °C.
    - where practical, use a magnetic stirrer set at low speed.
    - use OROTEMP gold plating solution. This is a pH neutral solution. Previous attempts to electroplate using a basic pH electroplate solution resulted in damage to the photoresist mask during the plate.
3. Optimum plating calls for 10 A/ft^2 . Most of our chips are small, with small plate areas. Usually 1-2 mA current is sufficient.
4. Plating for a duration of 30-40 minutes should result in a 10-20 μm thick gold layer.

Other comments:

- reversing polarity makes a good gold etcher.
- for critical applications where high quality gold pads are required, use a relatively large quantity of fresh plating solution.
- do not discard solution (it is expensive). Used solution can generally be reused in non-critical plating steps (like plating PCBs). Discard solution only after current quits flowing through it.

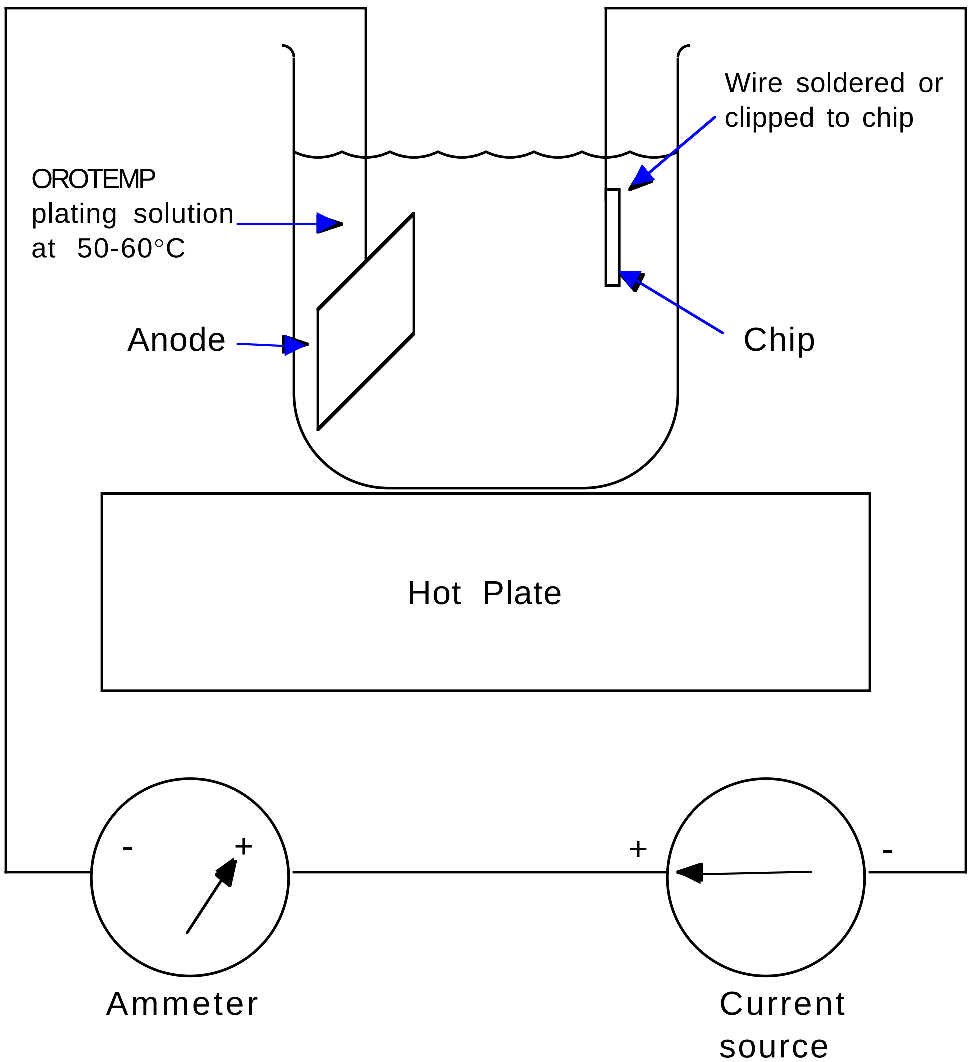

Fig. C.1: Electroplating setup.

Appendix D
CF_4 PLASMA PROCESS

This is a bi-layer resist process useful for doing lift-off and for forming photoresist bridges. It seems more reliable than the chlorobenzene soak process, but is more time consuming. The process utilizes two March Insruments (formerly Tegal) plasma chambers. These are table top barrel reactors designed for educational/research use. For operation, they require a mechanical vacuum pump and regulated gas sources.

Since reactive CF_4 etches glass, the pyrex cylinder in one of the units was replaced with an all teflon chamber. Within this chamber, samples were placed upon a perforated teflon plate. The substrate used to optimize this procedure was glass slide. This procedure works best with no more than 2 sq. inches total of substrate surface area, as there appears to be a loading effect in the teflon chamber when a larger area substrate is used.

1. Pre-Clean

   a. Clean slides in acetone, ethanol, H_2O. Bake dry.
   b. Full power O_2 plasma, 5 minutes. (O_2 at 600 mtorr, glass chamber; precede with a 5 minute O_2 flush).
   c. Note that each plasmod has its own vacuum gauge.
   d. You may need to skip this step if the chip already has a metal pattern on it (Au is okay, but Cr or Ag will oxidize).

2a. Photolith 1

   a. Apply adhesion promoter
      • apply enough to thoroughly cover chip
      • let stand 10 seconds before spinning
      • spin at 4000 rpm for 20 seconds
   b. Apply 1350J-SF photoresist (4000 rpm, 20 sec).
   c. Pre-bake 15 minutes at 75°C.
   d. Flood expose chips for 70 sec.; pause and blow off chips; expose another 70 sec.
      • Power incident on top of the mask from the HTG aligner is measured as 2.75mW/cm^2.

2b. TFE Chamber Preparation

a. While baking photoresist in step 2, evacuate the TFE chamber and flush with CF_4 for 5 minutes.

b. Run CF_4 plasma at setting 5.0 for ~3 minutes (see step 3).

• This “preps” the chamber and greatly improves run-to-run uniformity.

• This TFE plasmod will tend to drift in power, so continuous monitoring of the power is necessary. The fuse may blow if the needle pegs out.

3. CF_4 plasma

a. Place each chip in one of the 4 central-most squares scribed into the TFE flat support plate.

• chip placement in the chamber may be important.

b. Flush TFE chamber **5** minutes with 400 mtorr CF_4.

• it is important to remove all oxygen from the chamber to avoid pinholes.

• have had success with as little as 2 minutes of flush.

c. CF_4 plasma, **3** minutes at dial setting 5.0 (CF_4 @ 400 mtorr).

• This TFE plasmod will tend to drift in power, so continuous monitoring of the power is necessary. The fuse may blow if the needle pegs out.

• CF_4 plasma gives off a purplish glow.

d. Flush chamber 1 minute with 600 mtorr CF_4.

• this step is to protect the operator from possibly harmful gasses.

4. N_2 plasma roughing

a. Flush glass chamber at least **5** minutes with 600 mtorr N_2.

• it is critical that all O_2 be removed from the chamber. The fluorinized buffer layer is very thin and easily damaged by reactive O_2.

• have had success with only 2 minutes of flush.

b. Full power N_2 plasma, **25** seconds (N_2 @ 600 mtorr).

• N_2 plasma is necessary in order to get 2nd layer Photoresist to stick. If it doesn't stick, increase plasma time.

• too much N_2 plasma will put pinholes in the buffer layer. If pinholes are evident, decrease plasma time.

• N_2 plasma gives off a pinkish-red glow.

5. Photolith 2

a. Skip the adhesion promotion step.

• this step may damage the buffer layer.

• since this step is skipped, the 2nd photolith step needs to be done very soon after the N_2 roughing step, before moisture is absorbed.

b. Apply 1350J photoresist (4000 rpm, 20 seconds) (or 1350J-SF)

c. Prebake 20 minutes at 75 °C.

d. Expose through mask for 90 seconds at 6” contact vacuum.

e. Develop in 452 developer for 45-60 sec; gentle agitation. Double dip-rinse in HPH_2O.
- do not rinse under flowing water since the film may be damaged.

f. Blow dry.

6. Remove Buffer Layer

a. Flush glass chamber 5 minutes with 600 mtorr O_2.

b. Full O_2 plasma, **2** minutes (O_2 @ 600 mtorr).
- too much O_2 plasma may damage top layer and round corners.
- O_2 plasma gives off a blueish glow.

7. Etch Bottom Resist Layer

a. Etch for **45-60** seconds, gentle agitation, 452 developer.
- adjust etch to give desired undercut

b. Double dip-rinse in HPH_2O.

c. Gently blow-dry.
- Do not allow the chip to get hot after this step. I have seen the lip deform with as little as 5 min of 90°C heat.
- If all went well, your photoresist should appear very smooth at 400X magnification, and the overhang should be visible and consistent. Some slight roughness may be noted along the edges.
- A problem occasionally seen here by me and Bubba is what is thought to be pieces of residual buffer layer scattered about the chip (it will look like saran wrap under magnification).

8. (optional) Clean exposed surface.

a. Flush glass chamber 5 minutes with 600 mtorr O_2.

b. Full power O_2 plasma, 1 minute (O_2 @ 600 mtorr).

8. Metal deposition
9. Lift-off in acetone

Appendix E
STUVAC OPERATION

The STUVAC vacuum system in general consists of a roughing pump, a diffusion pump stack, a cryo-trap, and an 18” diameter, 18” tall glass cylinder. Materials can be evaporated from one of three e-gun hearths. Samples are place on a rotatable, tiltable, sample holder which is mounted on the top plate.

The following is a brief checklist to be followed whenever using the STUVAC vacuum system. This is <u>not</u> intended to be an operations manual for first time users of the system, but instead serves as a reminder of important things to do and not to do when operating STUVAC for people who are experienced users. The first time user of the system should be supervised through the process, as many ‘glitches’ in operation are better described physically rather than orally.

___ 1. Check XTAL monitor and turn on cylinder heat.
___ 2. Switch the auto/manual switch to auto. Press stop.
___ 3. Open both pneumatic and manual vents. The pneumatic vent by itself is very slow.
 • make sure the e-gun power supply is <u>locked</u> in the <u>off</u> position.
___ 4. After cylinder comes up to atmospheric pressure, lift the top plate pivot rod, and carefully open the top plate.
 • check the boot around the top of the cylinder. It will sometimes come loose here.
___ 5. Carefully raise the cylinder.
 • watch cables and pulleys.
 • do not raise too high! There is no ‘safety’ stop feature when raising the cylinder. I usually raise it until there is only about 3” of cable below the pulley.
___ 6. Remove chimney, source cover, and magnet shunt bar.
 • wear gloves and a mask.

___ 7. Load samples and note their location in the logbook.
___ 8. Install window, replace source cover and chimney.
___ 9. Carefully lower the cylinder.
___ 10 Load the sample holder.
___ 11. Close the top plate and lower the top plate pivot rod.
___ 12. Close all valves and inspect the top boot.
___ 13. Switch system to the auto mode and press start.

• there should be a 3-5 minute pump down before valves automatically switch.

___ 14. Fill the liquid nitrogen trap.
___ 15. Let system pump down for <u>at least</u> 45 minutes.
___ 16. Turn on the crystal monitor water, the e-gun water,and the ion gauge.
___ 17. Position the appropriate source.
___ 18. Unlock the e-gun switch, and turn on the e-gun.

• for safety sake, do not unlock the e-gun unless <u>both</u> PHILVAC <u>and</u> STUVAC are closed and under vacuum.

• make sure cables are connected to STUVAC.

• make sure interlock is switched to STUVAC.

___ 19. Turn on the crystal monitor and enter appropriate settings.

• make sure XTAL Monitor selector is set to STUVAC.

___ 20. Heat up the source, and set evaporation rate.

• only open shutter enough to expose XTAL monitor head.

___ 21. Open the shutter and evaporate.
___ 22. Turn off the e-gun and close shutter.
___ 23. For other sources, repeat step 17,19-22.
___ 24. Turn off the e-gun and lock out the switch.
___ 25. Turn off the crystal monitor, and crystal monitor water.
___ 26. Allow 10 minutes of cooling off time, then turn off the e-gun cooling water.
___ 27. Turn off the ion gauge.
___ 28. In auto mode, press stop.
___ 29. Open the manual vent, and turn off cylinder heat.

___ 30. After cylinder comes up to atmospheric pressure, lift the top plate pivot rod, and carefully open the top plate.

___ 31. Carefully remove sample from sample holder.

___ 32. Carefully raise the cylinder.

___ 33. Remove chimney, source cover, and discard coated window.

___ 34. Remove sources and replace magnet shunt bar.

___ 35. Install new window, replace source cover and chimney.

___ 36. Carefully lower the cylinder.

___ 37. Close the top plate, and lower the pivot bar.

___ 38. Close the manual vent valve.

___ 39. In auto mode, press start.

___ 40. After pumping system down for about 10 minutes, set system to standby state:
manual mode; only foreline valve open. May have to toggle this
valve switch to get it to open.

VITA

Stuart Martin Wentworth was born in Pensacola, Florida, on February 17, 1959, the son of Betty Joyce Wentworth and Martin Goodlough Wentworth. After graduating from Escambia High School, Pensacola, Florida, he attended Pensacola Junior College from 1977 to 1979. In March 1979, he entered Auburn University in Auburn, Alabama. In September of 1981, he wed Julie Leona Welch and returned with her to Auburn where he graduated with highest honors and a Bachelor's degree in Chemical Engineering. During the following years he was employed as a quality control engineer for Du Pont at Old Hickory, Tennessee. In January, 1985, he entered the Graduate School of The University of Texas at Austin. He received the degree of Master of Science in Engineering in August, 1987, and was admitted to candidacy in the Doctoral program at The University of Texas at Austin in July, 1988.

Permanent address:

29 Nottingham Way
Pensacola, Florida 32506

This manuscript was typed by the author.