National Défense
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THE EFFECTS OF GATE BIAS AND HYDROGEN ATMOSPHERE ON THE RADIATION RESPONSE OF THE MOSFET

by

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 88-21

PCN
0513E11

March 1988
Ottawa

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ABSTRACT

Metal Oxide Semiconductor Field Effect Tr [illegible]

The sensitivity of (MOSFET) radiation sensors has been measured as a function of gate-to-source bias. The observed sensitivity-bias relation can be explained in terms of hole/electron recombination, charge trapping and charge transport in the oxide. To explain post-irradiation increases in the MOSFET readings, negative-charge trapping and detrapping in the oxide is proposed.

The sensitivity of these MOSFETs has been found to be affected by the presence of hydrogen, indicating that hydrogen alters the trapping properties of the oxide. It may be possible to control the sensitivity of these sensors by controlling the hydrogen concentration at the time of hermetic packaging.

[illegible] Holes (Electron [illegible]), [illegible]

RESUME

Nous avons mesuré la sensibilité des détecteurs de radiation (MOSFET) en fonction du voltage du discriminateur-source; nous pouvons expliquer cette dépendance par la recombinaison trou/électron, par la rétention de la charge et par le mouvement de la charge dans l'oxyde. Afin d'expliquer les accroissements après-irradiation, nous vous proposons la théorie du piégeage et du dépiégeage de la charge négative dans l'oxyde des détecteurs (MOSFET).

Nous nous sommes aperçu que l'hydrogène affectait la sensibilité de ces détecteurs et changeait les propriétés de piégeage de l'oxyde. Il est possible de contrôler la sensibilité de ces détecteurs en réglant la concentration de l'hydrogène lors de l'emballage étanche.

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1.0 INTRODUCTION

Silicon/silicon dioxide

Ionizing radiation produces hole-electron pairs in the oxide layers of metal-oxide-semiconductor (MOS) structures, generally resulting in a permanent or semi-permanent positive charge being trapped in the oxide. In the absence of a large electric field, recombination reduces the charge separation but net positive charge density results from the high diffusivity of the electrons relative to the holes and from the predominance of hole traps in the oxide, particularly near the Si/SiO_2 interface of silicon-based devices. The presence of an electric field during irradiation facilitates separation of the holes and electrons, thus reducing recombination and redistributing (or removing) the charge.

The MOSFET (metal-oxide-semiconductor field-effect transistor) forms the basis of a very large number of analog and digital circuits. The introduction of charge in the dielectric (SiO_2) layer of this device alters its electrical characteristics and can lead to device failure. Charge trapped near the Si/SiO_2 interface is most effective in this respect. Positive charge trapping at the interface is enhanced by the application of a positive bias on the transistor gate during irradiation and high charge densities are made possible by the high density of positive charge traps.

Charge trapping can be employed for dosimetry purposes and is used in the MOSFET gamma-ray sensor being developed for an individual dosimeter for the Canadian Forces. For dosimetry purposes, permanancy of the trapped charge is essential. This report deals with some interesting and highly relevant aspects of the stability of the trapped charge and its relation to irradiation and post-irradiation bias and to the presence of hydrogen.

The usual measured characteristic of the MOSFET gamma-ray sensor is the gate-to-source voltage corresponding to specific source-to-drain current and voltage. The MOSFETs investigated here are dual devices which are designed to be used differentially. During irradiation, all terminals are normally connected together except for one gate which is biased positively. Measurements are made using equal current sources for each half. With drains and the reference gate at ground, the inputs of a differential amplifier are connected to the sources while the (inverted) output is fed back to the biased (during irradiation) gate. This establishes the sources at the source-to-gate voltage of the reference half and the biased-gate voltage at the differential gate voltage.

The measurements for this report were performed on 0.4-μm (oxide layer thickness) MOSFET sensors from two separate batches produced at Mitel Corp using a dry oxide growth process and a polysilicon gate. The sensors from the first batch were all packaged in ceramic dual-in-line packages. Those from the second batch were packaged in the same type of ceramic packages or in Cerdip packages which use a different sealing procedure. Both these packages provide a hermetic seal, but some tests were made with packages which were left unsealed or were opened after sealing.

Sensitivity of Sensors in Sealed Ceramic Packages

Significant differences were observed between the devices from the two batches both in sensitivity and in the drift in reading after irradiation, as noted in Ref (1). These batches were produced several months apart but, according to the manufacturer, there was no change in the carefully-monitored procedures used. The sensitivities as a function of irradiation bias are plotted in Fig 1 for measurements taken 1 day after irradiation. At positive bias, the response for sensors from the second batch are between 9 and 18% higher than those for the first batch. This may be due partly to a difference in oxide-layer thickness. The sensitivities at +200 V are above the maximum theoretical sensitivity of 6.8 mV/R for a 0.4-μm oxide, according to Ref (1), indicating that the thickness for both batches are greater than 0.4μ m. The response is seen to rise continuously with positive voltage V_B at a rate proportional to $\sqrt{V_B}$ up to about 20 V and to approach a maximum value at 200 V. In contrast, a maximum response is reported by Krantz et al (2) at about 5×10^5 V/cm for 0.022-μm MOS capacitors. This field would correspond to 20 V for a 0.4-μm oxide.

A larger response ratio (about a factor of two) between the two batches is noted for negative bias where the response for both batches is much less than for positive bias. This ratio indicates a definite difference between the properties of the oxide layers for the two batches.

For an individual dosimeter a compromise must be made between sensitivity and bias voltage. Most of the sensitivity measurements were made here with a bias of 5.6 V corresponding to that of two lithium-iodine cells which are being used in a proposed dosimeter.

In the sealed packages, the gate-to-source voltages for sensors from both batches were observed to increase for several days following irradiation as seen in Figs 2 and 3. Differences between the post-irradiation drift in readings again indicate differences in the properties of the oxide layers of the two batches. The difference in sensitivity at +5.6 V between the two batches is only 4% for the first pair of readings after irradiation but is increased to 13% one day later. These drift patterns were found to be essentially the same for post-irradiation biases of +5.6, 0 or -5.6 V. Since these increases are observed with both positive and negative gate voltages, they cannot be due to relocation of positive charge to trapping centres nearer the Si/SiO_2 interface. The increases may be due to detrapping of negative charge from the oxide, resulting in the removal of that charge with post-irradiation bias of either polarity. While positive charge trapping generally predominates in the oxide layer, negative charge trapping is also observed (see, for examples, Refs (3) and (4)) and negatively-charged interface states are induced by radiation (see Ref (5)). Smaller relative increases in readings observed at +200 and -200V are consistent with the removal of larger fractions of the unrecombined negative charge at the higher electric field.

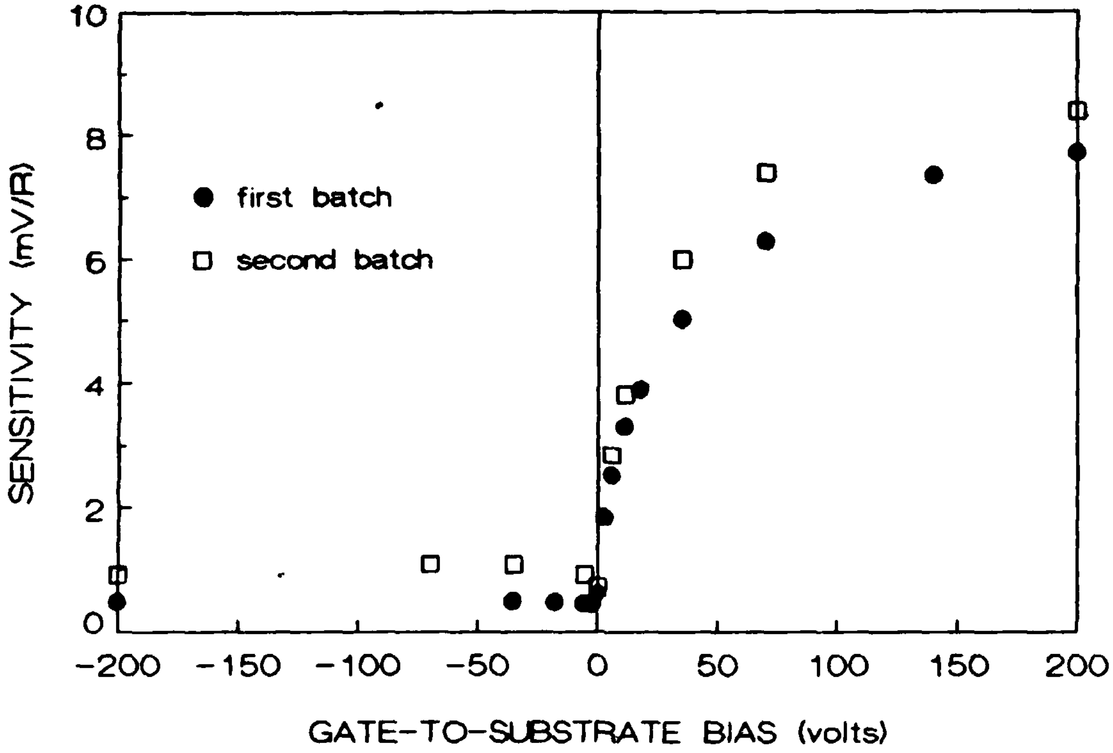

Figure 1. Radiation sensitivity of Mitel MOSFET as a function of gate-to-substrate voltage during irradiation. These sensitivities are based on readings taken one day after irradiation.

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                 DRIFT IN RADIATION SENSITIVITY

          BOARD# 33     WAFER# 17     THICKNESS .4 MICRON

      INITIAL READING # 21   WAS ON DAY 460.345
      IRRADIATION #      2   WAS ON DAY 461.346
      EXPOSURE IN R  202.0
      RATE IN R/H   1000.0
      BIAS IN VOLTS    5.6
      FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  22

      AVERAGE INITIAL READINGS :
       GATE-SOURCE-VOLTAGE = 3.1181 ( .2784) V    DIFF VOLTAGE =  .0002 ( .0043) V

      AVERAGE SENSITIVITY FOR BOARD # 33    ( 20 DEVICES )

        DAYS AFTER IRRAD      BIASED SIDE          UNBIASED SIDE          DIFFERENTIAL
              .003          2.3032 ( .0243)        .5378 ( .0051)       1.7654 ( .0213)
              .021          2.3353 ( .0245)        .5500 ( .0048)       1.7854 ( .0216)
              .070          2.3701 ( .0249)        .5673 ( .0049)       1.8028 ( .0220)
              .140          2.3860 ( .0256)        .5736 ( .0050)       1.8125 ( .0226)
              .289          2.4104 ( .0262)        .5852 ( .0052)       1.8252 ( .0230)
              .978          2.4605 ( .0293)        .6077 ( .0059)       1.8528 ( .0251)
             1.971          2.4884 ( .0307)        .6181 ( .0064)       1.8703 ( .0262)
             3.011          2.5017 ( .0320)        .6259 ( .0069)       1.8758 ( .0272)
             6.087          2.5362 ( .0365)        .6491 ( .0090)       1.8871 ( .0296)
            14.184          2.5657 ( .0389)        .6567 ( .0089)       1.9090 ( .0321)
            22.035          2.5810 ( .0397)        .6665 ( .0089)       1.9144 ( .0328)
            27.219          2.5822 ( .0403)        .6687 ( .0089)       1.9135 ( .0333)
            34.261          2.5854 ( .04;5)        .6713 ( .0092)       1.9141 ( .0339)
            43.048          2.6001 ( .0444)        .6788 ( .0096)       1.9213 ( .0365)
            59.102          2.6016 ( .0410)        .6831 ( .0098)       1.9185 ( .0331)
           142.116          2.6082 ( .0449)        .6876 ( .0102)       1.9207 ( .0363)
           167.040          2.6084 ( .0453)        .6943 ( .0111)       1.9141 ( .0360)
           255.245          2.6026 ( .0431)        .6870 ( .0100)       1.9156 ( .0351)
           332.248          2.5931 ( .0425)        .6862 ( .0097)       1.9068 ( .0347)
           411.120          2.5866 ( .0419)        .6800 ( .0092)       1.9066 ( .0347)
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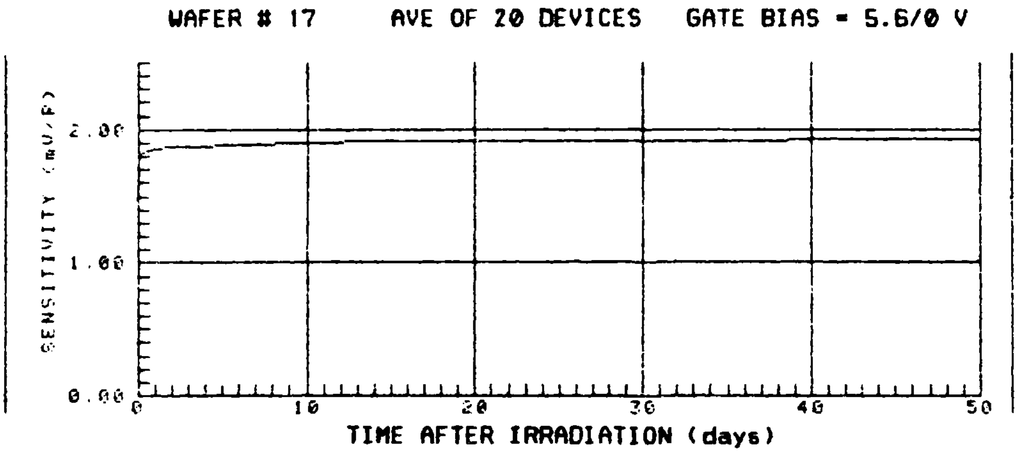

Figure 2 Measured radiation sensitivity in mV/R as a function of time after irradiation for MOSFETS from the first Mitel production batch, which were hermetically-packaged in a nitrogen atmosphere. The graph is for the differential sensitivity. Values in parentheses are the standard deviations from the mean for the twenty sensors on this board. The differential sensitivity increases by 5% in the first day and by an additional 3% in the next month.

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                 DRIFT IN RADIATION SENSITIVITY

     BOARD# 34      WAFER# 113      THICKNESS .4 MICRON

INITIAL READING # 21    WAS ON DAY 460.346
IRRADIATION #      2    WAS ON DAY 461.346
EXPOSURE IN R  202.0
RATE IN R/H   1000.0
BIAS IN VOLTS    5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  22

AVERAGE INITIAL READINGS :
 GATE-SOURCE-VOLTAGE = 3.0686 ( .0689) V    DIFF VOLTAGE =  .0011 ( .0018) V

AVERAGE SENSITIVITY FOR BOARD # 34    ( 20 DEVICES )

  DAYS AFTER IRRAD      BIASED SIDE        UNBIASED SIDE        DIFFERENTIAL
        .004          2.3925 ( .0214)      .6190 ( .0058)      1.7735 ( .0196)
        .021          2.4965 ( .0209)      .6412 ( .0053)      1.8553 ( .0197)
        .071          2.5951 ( .0217)      .6647 ( .0057)      1.9304 ( .0206)
        .141          2.6453 ( .0216)      .6732 ( .0053)      1.9721 ( .0210)
        .290          2.7021 ( .0227)      .6863 ( .0051)      2.0158 ( .0219)
        .979          2.7920 ( .0255)      .7076 ( .0060)      2.0844 ( .0240)
       1.970          2.8249 ( .0258)      .7146 ( .0057)      2.1103 ( .0247)
       3.011          2.8379 ( .0271)      .7192 ( .0058)      2.1187 ( .0254)
       6.085          2.8648 ( .0281)      .7366 ( .0060)      2.1282 ( .0265)
      14.182          2.8753 ( .0306)      .7378 ( .0058)      2.1376 ( .0287)
      22.034          2.8702 ( .0315)      .7426 ( .0064)      2.1275 ( .0300)
      27.220          2.8635 ( .0331)      .7426 ( .0059)      2.1209 ( .0306)
      34.261          2.8510 ( .0323)      .7430 ( .0061)      2.1079 ( .0299)
      43.048          2.8460 ( .0341)      .7485 ( .0067)      2.0974 ( .0315)
      59.102          2.8400 ( .0338)      .7511 ( .0061)      2.0888 ( .0318)
     142.117          2.8262 ( .0389)      .7502 ( .0065)      2.0760 ( .0362)
     167.041          2.8043 ( .0391)      .7550 ( .0068)      2.0493 ( .0364)
     255.246          2.7648 ( .0362)      .7478 ( .0060)      2.0170 ( .0336)
     332.249          2.7410 ( .0369)      .7458 ( .0066)      1.9952 ( .0344)
     411.121          2.7202 ( .0373)      .7394 ( .0063)      1.9808 ( .0347)
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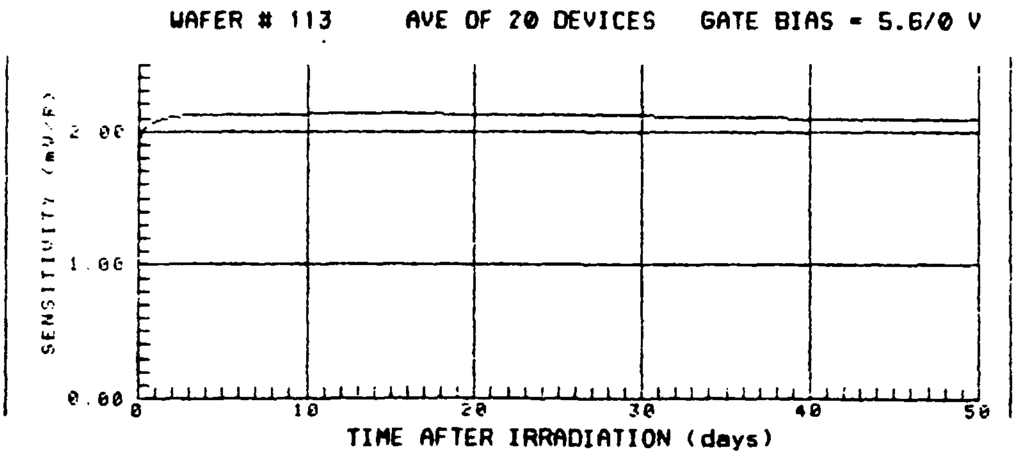

Figure 3. As for Fig 2 but for the second Mitel batch. For these sensors the increase is 18% in the first day and an additional 2% in the next few weeks. The initial values for the differential sensitivity are about the same for both batches but the increase is significantly larger for the second batch.

Sensitivity of Sensors in Unsealed Packages

Sensors in the ceramic packages, which had not been hermetically sealed or which had been sealed and reopened, had a lower sensitivity than those in the well-sealed packages. As rule, these sensors showed very little drift in readings for several days after irradiation. Typical drift patterns are seen in Figs 4 and 5. On first inspection these devices appear superior to the sealed devices. However, after several weeks the readings for sensors from the second batch were observed to drift upward inconsistently from device to device. The initial measurements showed the second-batch sensors to have about 10% lower sensitivity than those from the first batch, which is opposite to the relative responses for the sealed sensors.

While conducting experiments to improve the response of the MOSFET sensors as a function of photon energy, some of the sensors were potted in epoxy. These showed a relatively large post-irradiation drift in reading, as shown in Fig 6. Similar behaviour was not found when the sensors were potted in more inert materials such as silicone and granular alumina. On the presumption that hydrogen from the epoxy was diffusing into the oxide layer and affecting the charge trapping, some of the open sensors were exposed to hydrogen gas in a H_2 (25%)/N_2 (75%) mixture. Exposure to hydrogen before irradiation did not affect the MOSFET readings but resulted in enhancement of sensitivity. The times of exposure to and removal from the H_2/N_2 before irradiation indicated diffusion times on the order of an hour to a day.

Exposure to the H_2/N_2 mixture after irradiation demonstrates the effects of H_2 on the gate-to-source voltages. The sensors of Figs 7 and 8 were exposed to the H_2/N_2 mixture for one hour at one week after irradiation. A definite shift in reading was noted during that hour and further increases in the readings continued after removal from the H_2/N_2, as seen in the tables of these figures.

The post-irradiation shift in reading due to the hydrogen was found to be essentially the same for post-irradiation gate voltages of +5.6, 0 and -5.6 V; the fractional shift is less for irradiation bias of +200V than for 0- or +5.6-V bias; and, as seen in by comparison of Figs 7 and 8, the shift is much greater for sensors from the second batch than from the first batch.

Sensitivity of Sensors in Cerdip Packages

Most of these sensors, which were all from the second production batch, had the same sensitivities and inconsistent long-term drifts in reading as the unsealed sensors from the same batch. However, there were a number of exceptions for which the reading showed a sharp increase following irradiation as in Fig 9. These packages are not made to the same high standard of cleanliness as the ceramic packages and the anomalous behaviour may be due to the presence of contaminants.

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                DRIFT IN RADIATION SENSITIVITY

        BOARD# 32     WAFER# 17     THICKNESS .4 MICRON

INITIAL READING # 21   WAS ON DAY 454.362
IRRADIATION #      2   WAS ON DAY 454.382
EXPOSURE IN R  201.0
RATE IN R/H   1000.0
BIAS IN VOLTS    5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  22

AVERAGE INITIAL READINGS :
INCLUDING #  5
INCLUDING #  6
INCLUDING #  7
INCLUDING #  8
 GATE-SOURCE-VOLTAGE = 3.0825 ( .2147) V    DIFF VOLTAGE =  .0019 ( .0024) V

AVERAGE SENSITIVITY FOR BOARD # 32     ( 4 DEVICES )

  DAYS AFTER IRRAD      BIASED SIDE          UNBIASED SIDE          DIFFERENTIAL
         .006         2.2328 ( .0096)      .5030 ( .0031)      1.7298 ( .0067)
         .051         2.2332 ( .0094)      .5005 ( .0027)      1.7327 ( .0068)
         .175         2.2367 ( .0091)      .5029 ( .0024)      1.7339 ( .0069)
         .997         2.2395 ( .0092)      .5044 ( .0024)      1.7351 ( .0069)
        2.004         2.2440 ( .0097)      .5082 ( .0028)      1.7358 ( .0070)
        3.051         2.2456 ( .0099)      .5090 ( .0029)      1.7367 ( .0070)
        5.962         2.2586 ( .0097)      .5188 ( .0028)      1.7398 ( .0071)
        7.944         2.2679 ( .0101)      .5262 ( .0030)      1.7417 ( .0073)
        8.936         2.2673 ( .0097)      .5250 ( .0026)      1.7423 ( .0073)
       13.052         2.2933 ( .0110)      .5469 ( .0035)      1.7464 ( .0077)
       21.148         2.3076 ( .0106)      .5535 ( .0027)      1.7541 ( .0080)
       29.000         2.3241 ( .0111)      .5647 ( .0027)      1.7594 ( .0086)
       34.183         2.3303 ( .0105)      .5678 ( .0034)      1.7626 ( .0075)
       41.224         2.3364 ( .0100)      .5711 ( .0031)      1.7653 ( .0072)
       50.011         2.3465 ( .0113)      .5806 ( .0031)      1.7659 ( .0083)
      139.011         2.4023 ( .0127)      .6103 ( .0037)      1.7919 ( .0091)
      174.003         2.4088 ( .0130)      .6119 ( .0040)      1.7968 ( .0091)
      297.057         2.3994 ( .0115)      .6012 ( .0025)      1.7981 ( .0093)
      339.208         2.4017 ( .0113)      .6052 ( .0026)      1.7965 ( .0091)
      419.170         2.4103 ( .0141)      .6057 ( .0033)      1.8046 ( .0109)
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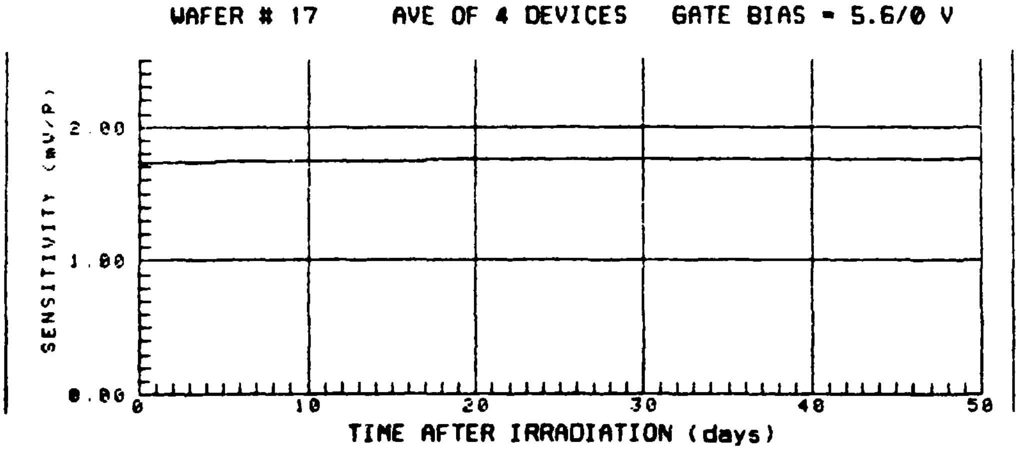

Figure 4. As for Fig 2 except that these sensors were in unsealed packages. These are seen to have a drift of only 4% over one year. However, this could vary with environmental factors such as humidity.

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               DRIFT IN RADIATION SENSITIVITY

     BOARD# 11      WAFER# 113     THICKNESS .4 MICRON

INITIAL READING #  7   WAS ON DAY 384.344
IRRADIATION #      1   WAS ON DAY 384.368
EXPOSURE IN R  200.0
RATE IN R/H   1000.0
BIAS IN VOLTS    5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  8

AVERAGE INITIAL READINGS :
INCLUDING #  17
INCLUDING #  18
INCLUDING #  19
INCLUDING #  20
 GATE-SOURCE-VOLTAGE = 3.0902 ( .0426) V    DIFF VOLTAGE =  .0035 ( .0026) V

AVERAGE SENSITIVITY FOR BOARD # 11    ( 4 DEVICES )

  DAYS AFTER IRRAD      BIASED SIDE         UNBIASED SIDE        DIFFERENTIAL
        .002          2.0911 ( .0094)      .5154 ( .0078)      1.5757 ( .0043)
        .038          2.0939 ( .0083)      .5134 ( .0073)      1.5806 ( .0043)
        .299          2.1011 ( .0068)      .5189 ( .0063)      1.5822 ( .0042)
        .985          2.1129 ( .0056)      .5278 ( .0058)      1.5851 ( .0042)
       1.992          2.1269 ( .0051)      .5376 ( .0054)      1.5893 ( .0040)
       3.106          2.1448 ( .0065)      .5511 ( .0060)      1.5937 ( .0045)
       6.073          2.1977 ( .0135)      .5826 ( .0066)      1.6151 ( .0092)
       9.102          2.2423 ( .0200)      .5921 ( .0072)      1.6502 ( .0173)
      13.081          2.2988 ( .0243)      .6045 ( .0080)      1.6943 ( .0234)
      21.033          2.3935 ( .0239)      .6160 ( .0085)      1.7775 ( .0246)
      35.305          2.4662 ( .0191)      .6269 ( .0084)      1.8393 ( .0197)
      62.218          2.5324 ( .0173)      .6383 ( .0086)      1.8942 ( .0182)
     104.091          2.6100 ( .0170)      .6589 ( .0084)      1.9511 ( .0170)
     136.082          2.6492 ( .0186)      .6744 ( .0091)      1.9749 ( .0143)
     161.170          2.6615 ( .0187)      .6853 ( .0092)      1.9763 ( .0166)
     220.015          2.6802 ( .0195)      .6919 ( .0094)      1.9883 ( .0168)
     283.244          2.6657 ( .0194)      .6870 ( .0098)      1.9787 ( .0170)
     328.337          2.6584 ( .0210)      .6846 ( .0085)      1.9737 ( .0169)
     489.186          2.6270 ( .0198)      .6876 ( .0083)      1.9394 ( .0177)
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WAFER # 113   AVE OF 4 DEVICES   GATE BIAS = 5.6/0 V

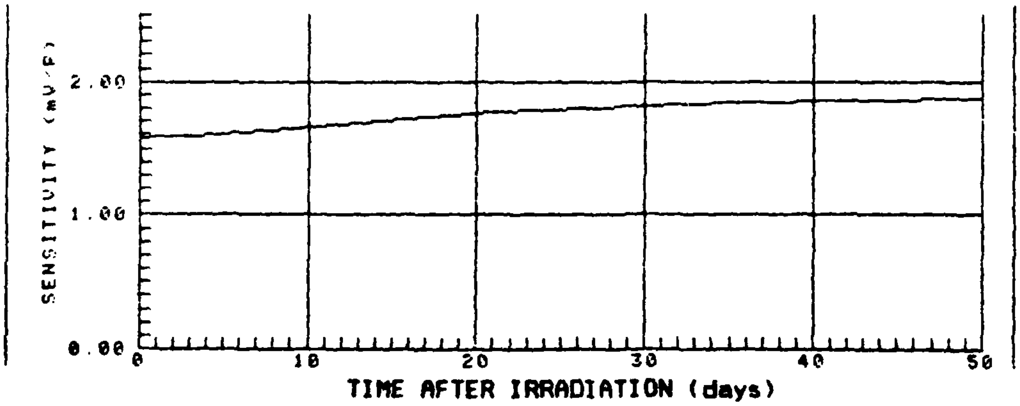

Figure 5. Sensitivity of unsealed sensors from the second batch. These sensors show little drift during the first few days after irradiation but the differential reading increases by 26% over several months. This is in contrast to the low drift seen in Fig 4 for unsealed sensors from the first batch.

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                    DRIFT IN RADIATION SENSITIVITY

            BOARD# 18      WAFER# 113      THICKNESS .4 MICRON

INITIAL READING #  2   WAS ON DAY 390.377
IRRADIATION #      1   WAS ON DAY 390.396
EXPOSURE IN R  198.0
RATE IN R/H   1000.0
BIAS IN VOLTS    5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  3

AVERAGE INITIAL READINGS :
INCLUDING #  1
INCLUDING #  2
 GATE-SOURCE-VOLTAGE = 3.1209 ( .0035) V    DIFF VOLTAGE =  .0044 ( .0032) V

AVERAGE SENSITIVITY FOR BOARD # 18    ( 2 DEVICES )

  DAYS AFTER IRRAD       BIASED SIDE          UNBIASED SIDE           DIFFERENTIAL
          .003        1.9081 ( .0221)        .4876 ( .0098)        1.4205 ( .0123)
          .043        2.0184 ( .0396)        .5212 ( .0121)        1.4972 ( .0275)
          .087        2.0549 ( .0455)        .5318 ( .0121)        1.5231 ( .0334)
          .166        2.1074 ( .0498)        .5452 ( .0119)        1.5622 ( .0379)
          .291        2.1561 ( .0463)        .5563 ( .0109)        1.5998 ( .0355)
          .967        2.2935 ( .0396)        .5813 ( .0086)        1.7122 ( .0310)
         3.073        2.3756 ( .0223)        .5980 ( .0081)        1.7776 ( .0142)
         4.186        2.3934 ( .0313)        .5831 ( .0109)        1.8104 ( .0204)
         6.964        2.4184 ( .0289)        .6043 ( .0083)        1.8141 ( .0206)
         9.981        2.4261 ( .0153)        .6119 ( .0073)        1.8142 ( .0080)
        14.271        2.4355 ( .0128)        .6141 ( .0076)        1.8214 ( .0052)
        21.148        2.4506 ( .0102)        .6227 ( .0061)        1.8281 ( .0041)
        29.277        2.4577 ( .0172)        .6192 ( .0066)        1.8385 ( .0107)
        42.059        2.4702 ( .0208)        .6242 ( .0061)        1.8460 ( .0148)
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WAFER # 113   AVE OF 2 DEVICES   GATE BIAS = 5.6/0 V

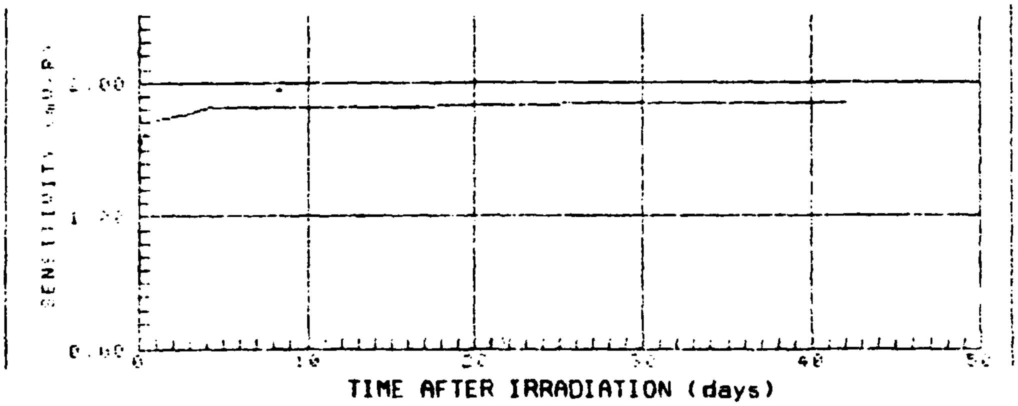

Figure 6. Sensitivity of sensors from the second batch, potted in epoxy. The sensitivity is reduced because of the greater electron stopping power of the epoxy compared with the ceramic lid of the package, but the increase in the post-irradiation reading closely resembles that of the sealed sensors of Fig 3.

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                    DRIFT IN RADIATION SENSITIVITY

        BOARD# 12      WAFER# 17      THICKNESS .4 MICRON

   INITIAL READING #  7   WAS ON DAY 761.491
   IRRADIATION #      1   WAS ON DAY 761.505
   EXPOSURE IN R  201.0
   RATE IN R/H   1000.0
   BIAS IN VOLTS    5.6
   FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  8

   AVERAGE INITIAL READINGS :
   INCLUDING #  7
   INCLUDING #  8
    GATE-SOURCE-VOLTAGE = 2.9318 ( .0066) V    DIFF VOLTAGE =  .0013 ( .0000) V

   AVERAGE SENSITIVITY FOR BOARD # 12    ( 2 DEVICES )

     DAYS AFTER IRRAD      BIASED SIDE          UNBIASED SIDE          DIFFERENTIAL
             .005        2.2326 ( .0016)       .4838 ( .0007)       1.7488 ( .0009)
             .016        2.2296 ( .0018)       .4821 ( .0010)       1.7475 ( .0008)
             .073        2.2382 ( .0021)       .4888 ( .0012)       1.7494 ( .0009)
             .235        2.2410 ( .0025)       .4915 ( .0015)       1.7495 ( .0010)
             .966        2.2460 ( .0026)       .4965 ( .0015)       1.7495 ( .0011)
            2.179        2.2529 ( .0027)       .5020 ( .0015)       1.7509 ( .0012)
            2.935        2.2593 ( .0024)       .5072 ( .0012)       1.7521 ( .0012)
            4.116        2.2640 ( .0028)       .5104 ( .0015)       1.7536 ( .0013)
            6.988        2.2790 ( .0031)       .5192 ( .0017)       1.7598 ( .0014)
            7.052        2.3427 ( .0030)       .5400 ( .0012)       1.8027 ( .0017)
            7.082        2.3979 ( .0037)       .5617 ( .0015)       1.8362 ( .0022)
            7.143        2.4539 ( .0026)       .5786 ( .0010)       1.8753 ( .0016)
            7.238        2.4957 ( .0061)       .5900 ( .0015)       1.9057 ( .0046)
            7.913        2.5458 ( .0073)       .6052 ( .0022)       1.9406 ( .0051)
            8.877        2.5472 ( .0082)       .6062 ( .0022)       1.9409 ( .0060)
           10.965        2.5491 ( .0067)       .6085 ( .0010)       1.9407 ( .0058)
           13.875        2.5491 ( .0070)       .6107 ( .0012)       1.9384 ( .0057)
           16.900        2.5400 ( .0071)       .6045 ( .0010)       1.9355 ( .0061)
           20.863        2.5425 ( .0083)       .6082 ( .0017)       1.9343 ( .0065)
          112.110        2.5323 ( .0019)       .6075 ( .0005)       1.9249 ( .0015)
```

WAFER # 17   AVE OF 2 DEVICES   GATE BIAS = 5.6/0 V

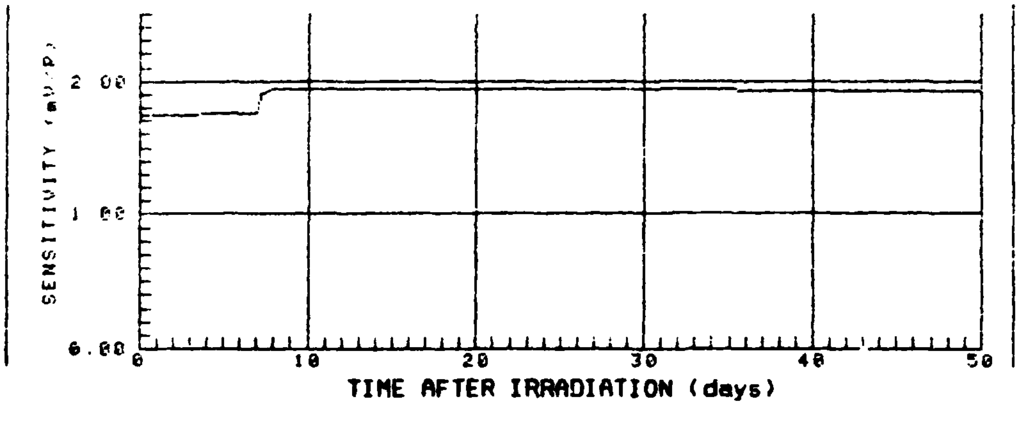

Figure 7 Change in measured sensitivity as a result of placing sensors from the first batch in a hydrogen/nitrogen atmosphere for about 1.5 hours on day 7 after irradiation. The differential reading increased by 2% while in the hydrogen/nitrogen mixture but continued to increase for several hours for a net increaes of 10%.

```
                    DRIFT IN RADIATION SENSITIVITY

          BOARD# 12      WAFER# 113      THICKNESS .4 MICRON

     INITIAL READING #  7    WAS ON DAY 761.491
     IRRADIATION #      1    WAS ON DAY 761.505
     EXPOSURE IN R   201.0
     RATE IN R/H    1000.0
     BIAS IN VOLTS     5.6
     FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  8

     AVERAGE INITIAL READINGS :
     INCLUDING #  3
     INCLUDING #  4
      GATE-SOURCE-VOLTAGE = 2.9584 ( .0200) V    DIFF VOLTAGE =  .0023 ( .0013) V

     AVERAGE SENSITIVITY FOR BOARD # 12    ( 2 DEVICES )

       DAYS AFTER IRRAD      BIASED SIDE         UNBIASED SIDE         DIFFERENTIAL
             .005          2.0779 ( .0215)       .5062 ( .0057)       1.5717 ( .0158)
             .016          2.0742 ( .0212)       .5035 ( .0055)       1.5707 ( .0158)
             .073          2.0754 ( .0213)       .5060 ( .0055)       1.5694 ( .0158)
             .235          2.0731 ( .0215)       .5047 ( .0057)       1.5683 ( .0157)
             .966          2.0762 ( .0207)       .5082 ( .0052)       1.5679 ( .0155)
            2.179          2.0827 ( .0206)       .5137 ( .0052)       1.5690 ( .0154)
            2.935          2.0884 ( .0206)       .5187 ( .0052)       1.5697 ( .0154)
            4.116          2.0937 ( .0203)       .5229 ( .0050)       1.5708 ( .0153)
            6.988          2.1112 ( .0199)       .5351 ( .0047)       1.5761 ( .0151)
            7.052          2.6136 ( .0275)       .6410 ( .0062)       1.9725 ( .0213)
            7.082          2.7509 ( .0322)       .6736 ( .0070)       2.0773 ( .0253)
            7.143          2.8388 ( .0269)       .6930 ( .0070)       2.1458 ( .0200)
            7.238          2.8912 ( .0357)       .7022 ( .0067)       2.1890 ( .0290)
            7.913          2.9299 ( .0363)       .7095 ( .0070)       2.2205 ( .0294)
            8.877          2.9208 ( .0371)       .7072 ( .0072)       2.2136 ( .0299)
           10.965          2.9125 ( .0357)       .7067 ( .0057)       2.2058 ( .0300)
           13.875          2.9054 ( .0380)       .7072 ( .0077)       2.1982 ( .0303)
           16.900          2.8891 ( .0352)       .6988 ( .0067)       2.1904 ( .0285)
           20.863          2.8858 ( .0361)       .7002 ( .0067)       2.1856 ( .0294)
          112.110          2.8406 ( .0245)       .6960 ( .0060)       2.1446 ( .0185)

                WAFER # 113     AVE OF 2 DEVICES   GATE BIAS = 5.6/0 V
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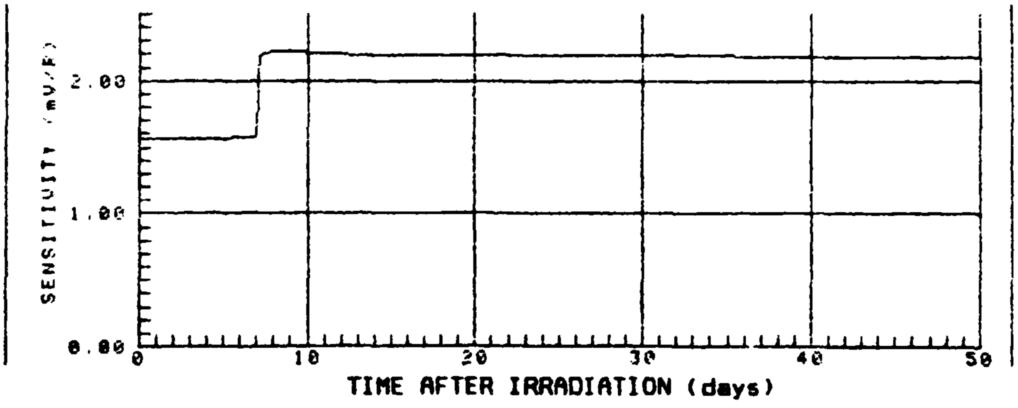

Figure 8. These sensors from the second batch were subjected to the same conditions as those from the first batch in Fig 7, but a much greater increase in reading was observed. For these sensors the increase in reading, while in the hydrogen/nitrogen mixture, was 25% and subsequent increase resulted in a total of 40%

```
                 DRIFT IN RADIATION SENSITIVITY

     BOARD# 10     WAFER# 100     THICKNESS .4 MICRON

INITIAL READING #  4   WAS ON DAY 320.571
IRRADIATION #      1   WAS ON DAY 321.550
EXPOSURE IN R  200.0
RATE IN R/H   1000.0
BIAS IN VOLTS    5.6
FIRST SET OF READINGS FOR SENSITIVITY MEASUREMENT IS  #  5

AVERAGE INITIAL READINGS :
INCLUDING #  4
 GATE-SOURCE-VOLTAGE = 3.0711 (0.0000) V    DIFF VOLTAGE =  .0004 (0.0000) V

AVERAGE SENSITIVITY FOR BOARD # 10    ( 1 DEVICE  )

  DAYS AFTER IRRAD      BIASED SIDE        UNBIASED SIDE        DIFFERENTIAL
         .008         2.1405 (0.0000)     .5495 (0.0000)     1.5910 (0.0000)
         .996         2.5541 (0.0000)     .6485 (0.0000)     1.9056 (0.0000)
        1.838         2.5892 (0.0000)     .6580 (0.0000)     1.9312 (0.0000)
        3.023         2.6204 (0.0000)     .6655 (0.0000)     1.9549 (0.0000)
        5.808         2.6537 (0.0000)     .6725 (0.0000)     1.9812 (0.0000)
        8.898         2.6678 (0.0000)     .6770 (0.0000)     1.9908 (0.0000)
       13.897         2.6827 (0.0000)     .6835 (0.0000)     1.9992 (0.0000)
       21.018         2.6982 (0.0000)     .6985 (0.0000)     1.9997 (0.0000)
       33.816         2.6860 (0.0000)     .6845 (0.0000)     2.0015 (0.0000)
       45.005         2.6822 (0.0000)     .6860 (0.0000)     1.9962 (0.0000)
       56.837         2.6708 (0.0000)     .6850 (0.0000)     1.9858 (0.0000)
       69.054         2.6740 (0.0000)     .6965 (0.0000)     1.9775 (0.0000)
      103.998         2.6550 (0.0000)     .6905 (0.0000)     1.9645 (0.0000)
```

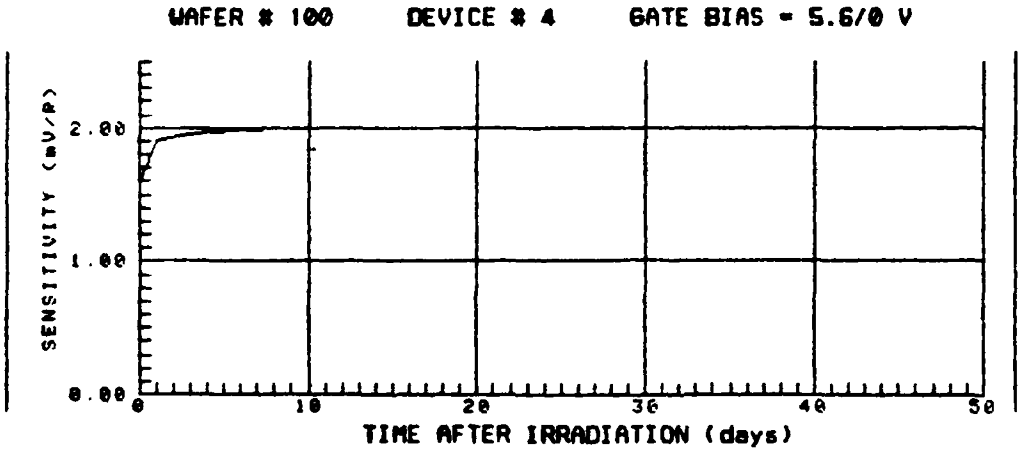

Figure 9. Most of the sensors packaged in the cerdip packages were found to have sensitivities similar to that of the unsealed sensors from the same (second) batch as shown in Fig 5. However, several of these showed more rapid increases in readings such as the above sensor.

Heating the sensors in these packages to 300° for 20 min, for example, before irradiation changed the sensitivity such that it often resembled that of the sensors sealed in the ceramic packages as discussed in Ref (1). (The sensors sealed in the ceramic packages and the unsealed sensors were essentially unaffected by heating before irradiation.)

Discussion of Results

The similarities between the hydrogen-induced shift for the unsealed sensors and the normal post-irradiation shift of the sealed sensors indicate that the same mechanism is involved. Detrapping and removal of negative charge was suggested above. The presence of an excess of hydrogen appears to accelerate this process. Several investigations (see, for example, Refs (6), (7) and (8)) have shown that the presence of hydrogen is an important factor in determining the radiation sensitivity of MOS devices.

Hydrogen can react with the defects in the noncrystalline SiO_2 and with the defects at the Si/SiO_2 interface (Refs (9) and (10)). Since these defects can be centres for charge trapping, the presence of hydrogen can alter the trapping centres and lead to the displacement of trapped charge. Experimentally, it was found for these MOSFETs that, at room temperature, hydrogen led to increases in the gate-to-source voltage of irradiated sensors indicating the removal of negative-charge trapping centres.

Differences between the sealed and unsealed sensors could possibly be due to a difference in oxygen concentrations since the sealing is done in a nitrogen atmosphere at about 400°C. Sensors which were irradiated within a few minutes of opening showed the same sensitivity as the sealed sensors, but sensors opened for 24 h before irradiation resembled the unsealed sensors.

Conclusions

The radiation sensitivity of the MOSFET sensors produced by Mitel were shown to increase continuously with positive irradiation bias up to the maximum voltage (200 V) at which measurements were made. At 200 V, the sensitivity is actually greater than the maximum calculated value, indicating that the thickness is greater than the expected $0.4 \mu m$. The sensitivity was shown to remain relatively small at negative voltages below 200 V.

Hermetically-sealed sensors consistently exhibited increases in post-irradiation readings of 5 to 10% of the radiation-induced voltage change during the first day and similar increases during the next few weeks. These increases were essentially the same for post-irradiation biases of +5.6, 0.0 and -5.6V. Minor, but distinct, differences in both sensitivity and post-irradiation drift were observed between two production batches.

The sensitivity of MOSFETs in unsealed packages was generally 10 to 20% lower than for the sealed devices. The unsealed sensors generally showed less post-irradiation drift than the sealed sensors but were more inconsistent in that respect. The presence of hydrogen led to increases in the readings of irradiated, unsealed sensors which brought their total radiation-induced shifts to approximately those of the sealed sensors.

The increase in the post-irradiation voltage and the lack of dependence of this increase on the sign of the post-irradiation bias indicate that detrapping of negative charge from the oxide or from interface states may occur. The presence of hydrogen apparently facilitates this process.

Differences between the sensitivities of the sealed and unsealed MOSFETs may be due to differences in the concentration of oxygen or hydrogen which affect the concentration of charge-trapping sites in the oxide or at the oxide/silicon interface.

Observed differences between sensors from the two production batches must be related to some subtle difference in the fabrication procedure or in the starting material, although no difference has been identified to us by the manufacturer. Experiments with the unsealed sensors indicate that it may be possible to control the sensitivity to some extent by post-production treatment, if necessary.

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The Effects of Gate Bias and Hydrogen Atmosphere on the Radiation Response of the MOSFET (U)

4. AUTHORS (Last name, first name, middle initial)

McGowan, S.

5. DATE OF PUBLICATION (month and year of publication of document)

June 1988

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

15

6b. NO. OF REFS (total cited in document)

10

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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The sensitivity of MOSFET radiation sensors has been measured as a function of gate-to-source bias. The observed sensitivity-bias relation can be explained in terms of hole/electron recombination, charge trapping and charge transport in the oxide. To explain post-irradiation increases in the MOSFET readings, negative-charge trapping and detrapping in the oxide is proposed.

The sensitivity of these MOSFETs has been found to be affected by the presence of hydrogen, indicating that hydrogen alters the trapping properties of the oxide. It may be possible to control the sensitivity of these sensors by controlling the hydrogen concentration at the time of hermetic packaging.

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