RADIATION EFFECTS ON GaAs CHARGE COUPLED DEVICES WITH HIGH RESISTIVITY GATE STRUCTURES

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ABSTRACT

The results of a study on the effects of 1 MeV electrons and 1 MeV neutrons on the operation of high speed GaAs Charge Coupled Devices (CCDs) are presented. Radiation-induced trapping levels are characterized using a linear array CCD structure and the periodic pulse technique. 1 MeV electron irradiation introduced traps at 0.1 eV and 0.39 eV with bulk trap introduction rates of 1 cm⁻¹ and 0.33 cm⁻¹, respectively. The devices were jrradiated to a maximum fluence of 9x10¹⁴ electrons/cm². 1 MeV neutron irradiation introduced an electron trap level at 0.64 eV with a bulk trap introduction rate of 0.5 cm⁻¹. Catastrophic device failure occurred at neutron fluences of 6x10¹⁵ neutrons/cm². Device charge transfer efficiency was characterized pre- and post-irradiation over the temperature range of 80 K to 300 K.

I. INTRODUCTION

A continuous high-resistivity Schottky barrier gate GaAs Charge Coupled Device (CCD) has recently been developed.¹ This new CCD structure has increased speed and dynamic range and is compatible with on-chip integration of the CCD support circuitry using FET technology. These advantages have stimulated interest in the development of structures using this approach for very high speed applications such as an agile bandpass filter which operates up to 2 GHz. With the planned use of these devices in military and space systems, the effects of radiation on the device characteristics is a matter of great interest. Previous studies on silicon CCDs have shown that the electrical properties of CCDs are significantly degraded by radiation.² High energy electron and neutron bombardment produce two primary effects in CCDs: 1) increased dark current density due to the introduction of generation centers, and 2) decreased charge transfer efficiency due to increased bulk trapping in the active region of the device.

An investigation of the effects of 15 MeV neutrons on large area capacitive gate GaAs CCD structures was recently reported.³ The authors reported a reduction in the charge transfer efficiency from 0.999 to 0.98 and an increase in the dark current density from 500 nA/cm² to 800 nA/cm² after irradiation to a fluence of 1.3x10¹⁴ neutrons/cm². The reduction in charge transfer efficiency was attributed to electron trap generation. To date, this work represents the only detailed radiation study on GaAs CCDs.

In this paper, results of a study of the effects of 1 MeV electrons and 1 MeV neutrons on the operation of a Resistive Gate CCD (RGCCD) are presented. The purpose of this study is twofold: 1) to gain insight into bulk trapping effects resulting from high energy particle radiation, and 2) to characterize the pre- and post-irradiation operation of a CCD which uses a new gate technology.

A. Device Description

The devices used in this work are 32-bit and 43-bit 4-phase RGCCDs. The devices were designed and developed at the Rockwell Microelectronics Research and Development Center, Thousand Oaks, California. The devices used in this study had epitaxial active regions fabricated by one of three processes: 1) Molecular Beam Epitaxy (device Lot 236); 2) Metallorganic Chemical Vapor Deposition (device Lot M01); and 3) Ion Implantation (device Lot C7-4). Details of the device structure are shown in Figure 1. The output buffer amplifier was integrated on-chip. The gates were 4.5 microns long x 100 microns wide for the 32 bit device and 6 microns long x 100 microns wide for the 43 bit device. The cermet film was sputtered CrSiO with a nominal sheet resistance of 1 Megohm/square. The active region was doped 6x10¹⁶ cm⁻³ n-type. The key difference between the resistive gate CCD and the conventional CCD is the gate structure. Instead of the interelectrode gap found in the conventional CCD, the metal electrodes are connected with a high resistivity cermet film. This film forms a Schottky barrier with the GaAs. The graded potentials at the surface of the device caused by the resistive film give greater fringing fields in the active region of the CCD which provide higher speed operation.

Figure 1. Resistive Gate CCD Circuit Diagram and Structure.
B. Periodic Pulse Technique

The periodic pulse technique was introduced by Mohsen and Tomsett as a means of analyzing the effects of bulk traps on the performance of buried channel CCDs. For the reader's convenience, the periodic pulse technique has the advantage of high sensitivity and measures defects in the active volume of the CCD which affect actual device performance. In this technique, a burst of charge packets is input to the CCD to fill traps throughout the buried channel layer. The initial burst is followed by a variable delay time, during which no charge is input to the CCD. If the characteristic emission time, $\tau$, of certain traps is less than the time between the pulse bursts, these traps will emit their trapped electrons. The empty traps then capture electrons from the first signal packet following the delay time. The charge lost from the signal packet is then a measure of the density of the trap level. Since the first charge packet following the delay time occupies the volume of one bit but loses charge to all empty traps in the entire active volume of the CCD, the CCD is very sensitive to bulk traps distributed in the buried channel layer. The total number of electrons lost from that charge packet is given by:

$$N_{loss} = mV_{sig}N_t[1-e^{-t/\tau}]$$  \hspace{1cm} (1)

where: $m =$ the number of CCD transfers
$V_{sig} =$ the pulse occupied by a single charge packet
$N_t =$ the density of the trap level
$\tau =$ the emission time constant of the trap

A fit of equation (1) to the experimental data from a point defect in an unirradiated GaAs CCD is shown in Figure 2. The bulk trap density can be obtained from the periodic pulse curve (Figure 2) for long times between bursts, i.e., $t>>\tau$, where equation (1) reduces to:

$$N_t = N_{loss}(max)/mV_{sig}$$  \hspace{1cm} (2)

For the data in Figure 2, the calculated trap density is $2.2\times10^{12}$ cm$^3$ ($m = 30$, $V_{sig} = 9.9\times10^{-9}$ cm$^3$).

The energy level of the bulk trap can be obtained from a temperature activation analysis of the bulk trap emission time constant, $\tau$, where $\tau$ is described by the equation:

$$\tau^{-1} = \sigma_nV_{th}N_c[\exp(-E_c-E_t)/kt]$$  \hspace{1cm} (3)

where: $\sigma_n =$ electron capture cross section of the trap
$V_{th} =$ average electron thermal velocity
$N_c =$ density of states in the conduction band
$(E_c-E_t) =$ energy of the trap level below the conduction band edge

Since the pre-exponential term in this equation is proportional to the square of absolute temperature,

$$T^2 = \sigma_nV_{th}N_c$$  \hspace{1cm} (4)

a plot of $\log(T^2\tau)$ vs $1000/T$ will yield $(E_c-E_t)$.

C. Test Facilities

A van de Graaff generator located at the Air Force Avionics Laboratory, at Wright Patterson AFB, Ohio was used as a source of 1 MeV electrons. The energy spectrum of the beam was nearly monoenergetic with a beam energy spread of approximately 40 keV. Devices were irradiated at room temperature with a beam current of 0.2 microamp/cm$^2$. No appreciable temperature rise was experienced by the device during irradiation.

The pulsed reactor at the Army Aberdeen Proving Ground, MD., was used as a source of neutrons. It gives a U-235 fission spectrum with a peak at 1 MeV. The devices were irradiated open circuit and experienced a temperature rise of 45$^\circ$K during irradiation.

Pre- and post-irradiation electrical characterization of the devices was performed at the Naval Research Laboratory, Washington, D.C. The periodic pulse measurements were made with the CCDs mounted in a dewar with temperature control of ±0.1$^\circ$K from 80$^\circ$K to 300$^\circ$K. Bulk traps with electron emission time constants from 60 microseconds to 1 second were investigated at all temperatures. Temperature activation analysis of the time constants was used to determine the trap energy levels. With these ranges of temperatures and time constants, it is possible to detect traps throughout the band gap. The clock frequency was limited to a maximum of 1 MHz by the experimental apparatus.

III. RESULTS

A. Pre-irradiation Traps

Traps observed prior to irradiation are due to the starting material and processing steps used to fabricate the device. Four major pre-irradiation traps were identified. They have been related to EL3, EL4, EL5 and EL7 which have been observed by other investigators. A summary of the activation energy plots used to calculate the energy levels is shown in Figure 3. Trap density and energy level for each device is shown in Table 1. These traps act as a background trapping level against which radiation induced-traps will be measured.

B. Dark Current

All devices were characterized for dark current prior to irradiation. Figure 4 is a plot of the range of dark currents measured for each lot of devices. The variation in dark current between lots was greater than three orders of magnitude. This condition indicates the strong processing dependence of this parameter. The
The lowest dark current measured on the MBE devices was 6x10^-6 A/cm² at room temperature. This is two orders of magnitude higher than the theoretically calculated value. A comparison with dark currents previously measured in capacitive gate devices shows that the high dark currents are due to leakage through the cermet Schottky barrier. These dark currents will be reduced as the cermet Schottky barrier process matures. Because it reduces dark current integration time, high frequency operation of this device will not be as susceptible to dark current degradation. However, the dark current present in these devices prevents measurements of trapping effects above 300°C.

C. Electron Irradiation-Induced Traps

Two electron trap levels were introduced by the 1 MeV electron irradiation. Following the notation of Lang, these levels will be designated E1 and E3. The E3 level observed here corresponds to the EL5 level which has also been observed by Martin, et al. in electron irradiated material. The activation energy plots which identified these levels are shown in Figure 5. Table II summarizes the radiation levels and trap densities for each device.

Table I. Pre-irradiation Trap Summary.

| DEVICE | ENERGY LEVEL (E_C-E_T) | DENSITY (traps/cm³) | LABEL |
|--------|------------------------|---------------------|-------|
| C7-4 #1 | 0.39 eV | 3.0x10^13 | EL 5 |
| C7-4 #2 | 0.39 eV | 1.0x10^13 | EL 5 |
| MO1 #2 | 0.54 eV | 4.0x10^13 | EL 3 |
| 236 #1 | 0.30 eV | 3.2x10^13 | EL 7 |
| 236 #2 | 0.40 eV | 6.0x10^13 | EL 4 |
| 236 #3 | 0.54 eV | 1.0x10^13 | EL 3 |
| 236 #8 | 0.28 eV | 3.6x10^13 | EL 7 |
| 236 #9 | 0.41 eV | 4.0x10^13 | EL 4 |
| 236 #10 | 0.54 eV | 1.0x10^13 | EL 3 |
| 236 #12 | 0.30 eV | 1.0x10^13 | EL 7 |
| 236 #12 | 0.41 eV | 1.0x10^13 | EL 4 |

Figure 3. Activation Energy Plot for Pre-irradiation Traps.

Figure 4. Dark Current Variation Between Lots and Within Lots.
The doped and undoped results are plotted in Figure 5. The introduction rate of this device was approximately 10 cm⁻³.

The average level measured for E₃ was 0.39 eV as shown in Figure 5. Pons reported this level at 0.35 eV using the DLTS measurement technique. A bulk trap introduction rate of 0.33 cm⁻¹ was calculated from the data of Table II plotted in Figure 7. Pons reported a value of 0.39 cm⁻¹.

Table II. Electron Irradiation Trap Summary.

| DEVICE | FLUENCE (electrons/cm²) | TRAP ENERGY LEVEL | TRAP DENSITY (traps/cm³) | LABEL |
|--------|--------------------------|-------------------|--------------------------|-------|
| MO1 #2C | 2x10¹⁴ | 0.096 eV | 2.6x10¹⁴ | E₁ |
| | 0.37 eV | 5.7x10¹⁴ | E₂ or E₅ |
| | 0.106 eV | 4.9x10¹⁴ | E₁ |
| | 0.37 eV | 1.2x10¹⁴ | E₂ or E₅ |
| | ~0.10 eV | 8.0x10¹⁴ | E₁ |
| | 0.365 eV | 2.0x10¹⁴ | E₂ or E₅ |
| 236 #6 | 2x10¹⁴ | 0.090 eV | 8.8x10¹⁴ | E₁ |
| | 0.091 eV | 2.1x10¹⁴ | E₁ |
| | ~0.39 eV | 1.1x10¹⁴ | E₂ or E₅ |
| 236 #9 | 2x10¹⁴ | 0.087 eV | 1.2x10¹⁴ | E₁ |
| | ~0.39 eV | 9.0x10¹⁴ | E₂ or E₅ |
| | 0.098 eV | 2.3x10¹⁴ | E₁ |
| | ~0.39 eV | 1.3x10¹⁴ | E₂ or E₅ |
| | ~0.1 eV | 4.8x10¹⁴ | E₁ |
| | 0.39 eV | 2.0x10¹⁴ | E₂ or E₅ |
| | 1x10¹⁴ | 0.10 eV | 1.9x10¹⁴ | E₁ |
| | 3x10¹⁴ | 0.11 eV | 2.4x10¹⁴ | E₁ |
| | 9x10¹⁴ | 0.116 eV | 7.1x10¹⁴ | E₁ |

Figure 6. Trap Density vs 1 MeV Electron Fluence (Eₖ = 0.1 eV).

Figure 7. Trap Density vs 1 MeV Electron Fluence (Eₖ = 0.38 eV).

D. Neutron Irradiation-Induced Trap

One bulk electron trap was induced as a result of 1 MeV neutron irradiation. The activation energy plot showing N₁ at 0.64 eV is shown in Figure 5. The trap energy levels and densities for each device are shown in Table III. Due to pre-irradiation traps E₃ and E₄, the data for N₁ was difficult to interpret. Only neutron fluences of 6x10¹³ cm⁻² could changes in charge transfer efficiency be measured which were clearly the result of neutron irradiation and not the
Table III. Neutron Irradiation Trap Summary.

| DEVICE | FLUENCE (neutrons/cm²) | TRAP ENERGY LEVEL (eV) | TRAP DENSITY (traps/cm³) |
|--------|------------------------|------------------------|--------------------------|
| 236 #1 | 6x10¹³                 | 0.82                   | 3.5x10¹³                 |
| 236 #2 | 6x10¹³                 | 0.855                  | 3.0x10¹³                 |
| C7-4 #1| 5x10¹³                 |                        |                          |

The result of pre-irradiation traps EL3 and EL4. The NI energy level observed corresponds to that observed by Jenkins. The data on the ion implanted device (Lot C7-4) was of insufficient accuracy to calculate trap densities. A fluence level of 1.6x10¹⁴ neutrons/cm² was attempted; however, all devices were lost due to radiation-induced shorts. A trap introduction rate of 0.5 cm⁻¹ was measured. Jenkins recently reported a rate of 3.5 cm⁻¹ using 15 MeV neutrons which is similar to that seen by earlier investigators in GaAs FET devices. Poll reported a bulk damage ratio of 2.5 for 14 MeV neutrons to 1 MeV neutrons in silicon devices. The low energy spectrum neutrons in this effort could account for some of the difference.

E. Charge Transfer Inefficiency

The periodic pulse data was also used to calculate the charge transfer inefficiency (CTI) of each device, for both pre- and post-irradiation conditions. A typical plot for the electron irradiated device is shown in Figure 8. The change in CTI due to EI is very strong in the temperature range 80°K to 120°K. Above 120°K, the emission time constant for EI becomes smaller than the period of the clock, thus resulting in no effect on the CTI. The effects of EL7 begin to appear at temperatures above 160°K with EL3, EL4, and EL5 all contributing to higher CTI as temperature increases. The worst-case, pre-irradiation CTI for these devices ranged from 0.0005 at lower temperatures to 0.01 for temperatures in the range 250°K to 300°K. The effects of radiation on CTI can be seen in Figure 9. The linear trap introduction rate is reflected in the linear relationship between CTI and electron fluence. The values of CTI at which a device is no longer useful is highly dependent upon the application.

IV. SUMMARY AND CONCLUSIONS

The periodic pulse technique has proven to be a powerful tool for characterizing the newly developed resistive gate technology for GaAs CCDs. Bulk electron traps could be detected down to densities of 1x10¹³ cm⁻³. Electron traps EL3, EL4, EL5 and EL7 were observed prior to irradiation.

Electron traps EI and E3 at 0.1 eV and 0.39 eV were measured following 1 MeV electron irradiation at fluence levels up to 6x10¹⁴ e⁻/cm². Bulk trap introduction rates of 1 cm⁻¹ for EI and 0.25 cm⁻¹ for E3 were measured. Changes in device CTI due to radiation bulk damage were plotted over the full temperature range of measurement. Devices operating at low temperatures will be severely degraded by the EI trap. After a fluence of 2x10¹⁴ e⁻/cm², the CTI at 80°K has increased to 0.01 which is not acceptable for many circuit applications.

One MeV neutron irradiation introduced an electron trap level at 0.64 eV, and a bulk trap introduction rate of 0.5 cm⁻¹ was measured. Due to radiation-induced device failure, measurements at neutron fluences greater than 6x10¹³ cm⁻² could not be made.
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