Displacement damages created by γ particles radiation in n type GaAs.

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In this work, we present a study of the effect of γ particles radiation in n type gallium arsenide (GaAs) doped with silicon (Si_{Ga}). For this, we have irradiated samples of GaAs doped with $10^{15}cm^{-3}$ and $10^{16}cm^{-3}$ of Si_{Ga} at different fluences of γ radiation. We have used photoluminescence (PL) measurement at 8.8K to identify defects induced by γ radiation in these samples. We found that this type of radiation induces the gallium vacancy V_{Ga} in GaAs and causes the transfer of the silicone impurity from Ga site to As site. These two defects are displacement damages created by γ radiation and are the same of displacement damages created by the other type of radiation (charged particles and neutral particles). The difference between the effect of particles is the introduction rate b of the defect. Then, we found that b of γ particles is ten times weaker than 7MeV electron particles. γ ray are photons, so they can't interact with GaAs atoms to product displacement damages by Rutherford diffusion (charged particles) or diffusion from hard spheres model (neutral particles). We suggest that recoil electrons produced in GaAs by photoelectric effect and Compton effect are responsible to the creation of these displacement damages. Indeed, these electrons have enough energy (~ 1 MeV) to product the same damages.

PACS number(s): 61.80

I. INTRODUCTION

There have been several reports on the effect of the radiation with charged particles and neutral particles in n type gallium arsenide (GaAs) doped with silicon impurity [1-4]. All this reports indicates that the radiation introduces displacement damages in n type GaAs and the mechanism of creation of these damages are Rutherford diffusion in the case of charged particles or diffusion from hard spheres model for neutral particles [5]. Indeed, it have been reported that radiation with these type of particles induces punctual defects such gallium vacancies, causes the transfer of the silicon impurity from Ga site to As site and also introduces other complex of defects [6]. All these atomic displacements are responsible to the degradation of electrical and optical properties of this material [7]. This degradation is a function to nature and the energy of target particles and it was correlated with introduction rate of the displacement damages induced by radiation. Also, it has been reported that γ particles radiation causes à degradation of electrical and optical properties [7]. These authors have suggest that this type of radiation induced in n-GaAs a displacement damages without showing the chemical nature of microscopic damage responsible to this change.

We show in the present work that the signature of V_{Ga} and Si_{As} can also be detected in photoluminescence spectra recorded with n type GaAs doped with Si_{Ga} irradiated with ^{60}Co γ particles. We also purpose the microscopic mechanism of the creation of these displacement damages. Indeed we're going to show that there are recoil electrons created with Compton effect in GaAs by γ particles which can be responsible to the creation of these displacement damages.

II. EXPERIMENTAL.

A. Samples

The MOCVD samples studied in this work were obtained from the Epictronics corporation in Phoenix, AZ. A 2µm buffer layer was deposited on undoped semi-insulating GaAs 625µm thick wafer 3 inches in diameter, and a 4 µm active layer was grown on top. The samples were n-doped nominally to 0 (intentionally undoped), 10^{15} and 2×10^{16} Si_{Ga}/cm^3 . Transport measurements revealed that at room temperature, N_D-N_A were the same of the nominal doping.

The ^{60}Co γ particles irradiation was performed at Aberdeen Proving Ground (Aberdeen, MD) fast burst reactor. The dose of these particles was determined with thermoluminescent dosimeters (TLD). The irradiation was performed from 1krad up to 1Grad. The reason for this large range is because there was no effect of radiation observed for doses less than 10 Mrad. Although the PL intensity began to drop at this dose but no new structures were observed in PL spectra for this irradiated samples.

In this investigation, the annealing was performed at 550°C for 30 minutes. A major effect of annealing is to dissociate complexes that exist in samples. By systematically varying the anneal temperature, we observed that in irradiated samples only, the peak associated to V_{Ga} increased abruptly at 450°C [8], indicating that V_{Ga} is dissociated from a complex at this temperature. Another consequence of the annealing is that the PL intensity tends to be restored.

B. Photoluminescence

In this standard method often used to identify defects in semiconductors, the electronic population is altered with laser excitation. As the electrons return to lower states energy they may emit photons and phonons, whose energy corresponds to states within the gap. In our experiments, the incident photon energy was larger than the band gap. Most of our measurements were performed at 8.8 K in order to reduce the role of phonons. Since GaAs is a direct gap semiconductor, the structures observed in PL consist of transitions from the conduction band to acceptors states (e-A), from donor states to the valence band (D-h), donor acceptor pairs (DAP) and excitonic transitions. Because the electronic effective mass is much smaller than the hole effective mass, the donor states are closer to the conduction band than the acceptor states are to the valence band. Another consequence is that the donor states tend to be bunched together whereas the acceptor states are more spread out.

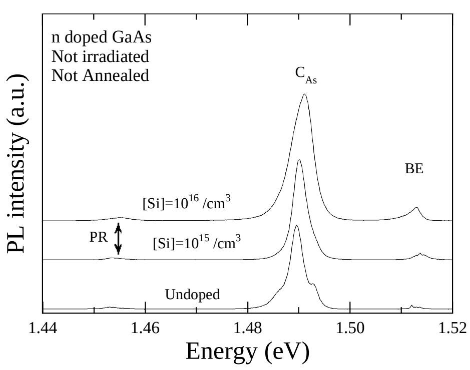

Fig. 1: PL spectra for unirradiated samples. We observe in these spectra three structures. The bound exciton structures noted BE which contains also the signature of Si_{Ga} to valence band transition. C_{As} structure attributed to conduction band to A_s acceptor level transition and it phonon replica PR. We remark that the broadening of these structures increases with the doping.

One method of identifying a substitutional defect is to increase this defect in a systematic way and to look for a PL transition whose intensity increases in linear proportion. Using this principle, it was found that Si, when replacing Ga, (Si_{Ga}) gives rise to a donor state whose energy lies at about 5.9 meV below the conduction band [9, 10]. The gap of GaAs is 1.519 eV; the PL signature of Si_{Ga} is a signal at about 1.513 eV. Unfortunately other donors are also present in this energy range and one observes bound excitons. Similarly, Si, when replacing As, (Si_{As}) gives rise to an acceptor state whose energy is 34.5 meV above the valence band [11]. Thus the PL signature of Si_{As} is a signal at 1.484 eV, which corresponds to a transition from the conduction band to one associated with Si_{As}.

In figure 1 we show a typical PL spectra of unirradiated samples of GaAs doped with Si_{Ga} impurities. We observe in these spectra three principle structures. The bound exciton structures noted BE which contains also the signature of Si_{Ga} to the valence band. C_{As} structures attributed conduction band to C_{As} acceptor level transition and it phonon replica PR.

III. CHARGED AND NEURAL PARTICLES RADIATION EFFECTS ON SEMICONDUCTORS.

The mechanism of displacement damages introduction with charged particles and neutral particles has described in previous works [2, 5, 12] For charged particles, the behavior of the introduction rate of V_{Ga} and Si_{As} (b) in n type GaAs with the energy is in E^{-1} law. For neutral particles b has been found to be a constant. So, when an energetic charged and neutral particle passes through the matter, they interact with it atoms by Rutherford diffusion and a hard spheres model scattering respectively [5]. These results have been found by photoluminescence measurements performed on n type GaAs irradiated by different type of radiation and annealed at 550°C [2].

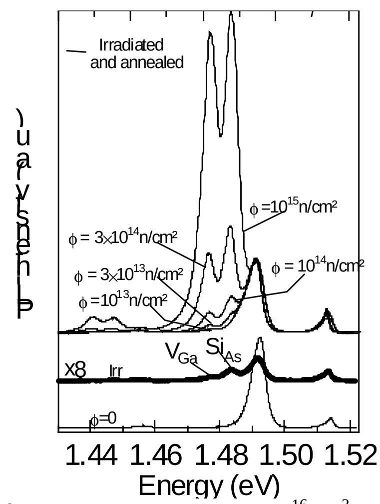

Fig. 2: PL of GaAs samples doped at 10^{16}cm^{-3}.as reported in reference 6. The lowest traces are for unirradiated sample. The second is for irradiation to 10^{15} cm^{-2}. The top five are for irradiated and annealed samples. In the top five the intensity is normalized to that of carbon.

The figure 2 as reported in reference 6 shows the PL spectra recorded for GaAs doped at 10^{16} Si_{Ga}/cm^3 irradiated with 1 MeV neutron particles and annealed at 550°C. At the bottom the spectrum correspond to unirradiated samples. The second is for irradiation to 10^{15}cm^{-2}. We note the apparition of two new peaks at 1.475eV, which is the signature of VGa, and 1.484eV, which is the signature of Si_{As}. Irradiation reduces the PL intensity, but eight have multiplied it in order to show the new structures induced by irradiation. The top five traces are for irradiated and annealed samples. Annealing restores most of PL intensity. In the top five the intensity is normalized to that of carbon. Let us denote by I(C) the PL intensity associated with the carbon acceptor impurity, by I (V_{Ga}) that related to V_{Ga} and I (Si_{As}) that related to Si_{As} induced by radiation. The slope of the ration of the I (V_{Ga})/I(C) or I (Si_{As})/I(C) as a function of fluence ϕ has been correlated with the introduction rate b of these displacement damages [2]

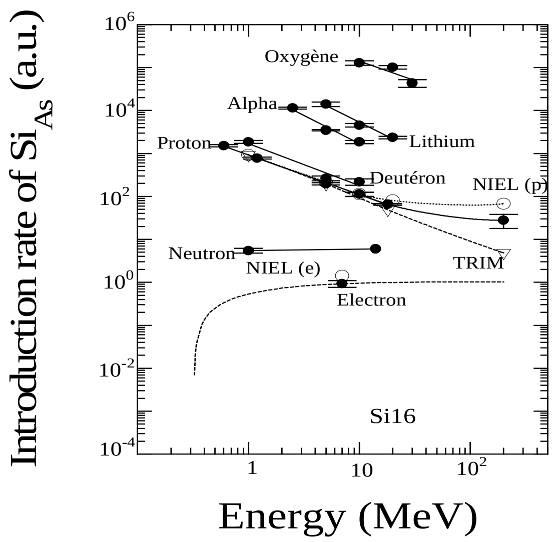

Fig. 3: Introduction rate of Si_{As} for samples of GaAs doped to $10^{16}cm^{-3}$ irradiated and annealed as a function of energy of different particles as reported in reference 2. The results of some simulation methods (NIEL and TRIM) are also included to compare theoretical and experimental results.

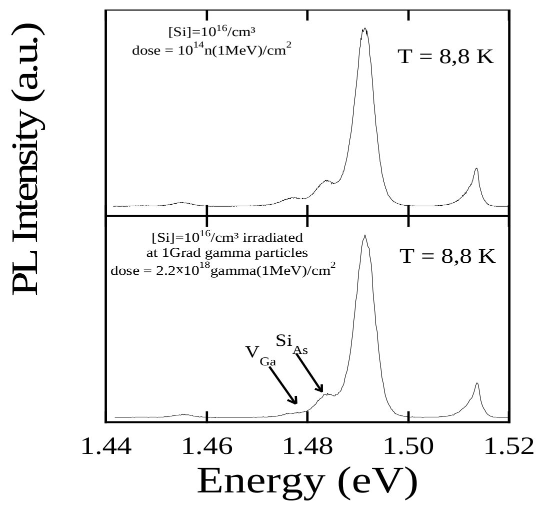

Fig. 4: Comparison between PL spectrum recorded samples doped at $10^{16}cm^{-3}$ and irradiated with γ ray and same samples irradiated by 1MeV neutron particles. We remark that the damages produced by γ ray at 1Grad dose ($\phi=2.2\times10^{18}\gamma/cm^2$) and 1 MeV neutron particles at $\phi= 10^{14}n/m^2$ are the same. It suggests that 1MeV-neutron particles are 22000 fold more damaging than γ rays.

The figure 3 as reported in reference 2 shows the behavior of the introduction rate b with nature and energy of particles. For the proton, the introduction rate follows approximately the E^{-1} dependence of Rutherford scattering up to 10 MeV, although there is some dependence on the sample doping. The higher energy points, though few suggest a deviation from E^{-1} relation. It has been suggest that nuclear reactions are responsible for the increase in damage rate at high energy according to Non Ionization Energy Loss simulations (NIEL) [1]. But experimentally, with our measurement, it has been found that NIEL overestimates this deviation. We thus have suggested another mechanism. We recall that an incident particle of mass m_1, imparts at maximum $4m_1/m_2$ of its energy to a particle of mass m_2. For 200 MeV protons incident on GaAs, this comes to approximately at 10 MeV. Hence the recoil atoms are very damaging. We suggest that the increase in introduction rate at high energies is due to recoil atoms, whose effect masks nuclear reactions.

For the heavy ions it was also expected principally the Rutherford scattering mechanism to be responsible for the displacement damage. The energy of the introduction rates agrees qualitatively with this view. One expects linear dependence on mass of the projectile and quadratically on the number of charges.

IV. RESULTS OF ^{60}Co γ RAY PARTICLES.

The effect of ^{60} Co γ particles has been tested in GaAs doped at $10^{15}Si_{Ga}/cm^3$ and $10^{16}Si_{Ga}/cm^3$. We have irradiated at the same time the same samples with 1 MeV neutron particles for the lesser doping; there were no new peaks in the PL spectrum recorded with samples irradiated with γ particles. But the PL intensity began to drop at very high dose (1Grad).

When the radiation particle is very damaging the PL spectrum is reduced to electronic noises at high fluences. So there is no PL peaks at all in the spectrum. This type of radiation induces a high density of complex and the punctual defects. The γ particles are not very damaging and the PL signal began to drop at 10 Mrad in samples doped to $10^{16}cm^{-3}$. At the highest doses that we have (1Grad), the PL signal has drop to but no new peak. Annealing restores considerably the intensity of the PL spectrum. Figure 4 shows the PL spectrum of GaAs doped to $10^{16}cm^{-3}$, which have been irradiated and then annealed. Since the annealing dissociates complexes induced by radiation, we attribute the partial restoration of the PL intensity to the dissociation of those complexes whose energy lies at mid-gap. The nature of these complexes is not known, but V_{Ga} and Si_{As} appears in these spectra after annealing, indicating that the complexes contain V_{Ga} and Si_{As}. In this figure we show at the bottom the effect of γ particles radiation at 1 Grad doses. This dose is equivalent to $\phi=2.2\times10^{18}\gamma$(photons)/cm^2 [13]. We remark at this fluence, that radiation with γ particles induces displacement damages such V_{Ga} and Si_{As} which are indicated by an arrow in the figure. We doesn't have a lot of points to plot I (V_{Ga})/I(C) or I (Si_{As})/I(C) versus ϕ for having the introduction rate b for γ ray. In order to have b, we report at the top of the figure the PL spectrum for the same sample irradiated at the same conditions with 1MeV neutron particles and annealed at 550°C. The fluence was $\phi=1.02\times10^{14}/cm^2$. These spectra are qualitatively the same. It suggests that neutron particles are 22000 fold more efficient to induce displacement damages than γ particles.

V. DISCUSSION.

Since the γ rays are photons. So they are particles without mass or charges. And, it is well known that displacement damage occurs in GaAs by a Rutherford scattering in the case of charged particles or hard spheres model scattering in the case of neutral particles. So, what the scattering process which is responsible to the creation of these displacement damages in the case of γ particles? The observation of V_{Ga} and Si_{As} in γ irradiated GaAs confirms that displacement damage does occur in γ irradiated material and gives a microscopic explanation for the degradation of macroscopic properties observed in γ particles irradiated semiconductors.

The energy transferred from γ particles radiation to the semiconductor atoms is so weak for product displacement damages [14]. It is known that a γ ray knocks out an electron through the Compton effect, which can knock out an atom [12, 14]. Indeed, these Compton electrons which have slightly 1 MeV at the energy [14] are able to induce V_{Ga} and Si_{As} in GaAs. Because the lowest electron energy that we need for producing displacement damage is 0.25 MeV [15].

Since the linear attenuation coefficient for Compton process is slightly μ=1cm^{-1}[14]. The thickness of the active layer for our GaAs samples is 4μm. So, in our samples, we must have 10^4 photons or γ particles for producing 1 Compton electron. We do observe Si_{As} and V_{Ga} in irradiated samples at 1Grad dose which is equivalent to $\phi=2.2\times10^{18}\gamma$(photons)/cm^2. This dose product in our samples 2.2×10^{14} Compton electrons. In our investigation in the reference [2], we have reported that 1 MeV neutron particles are more damaging than 7 MeV electron particles. We also reported that the PL spectra recorded on GaAs doped at 10^{16}cm^{-3} and irradiated respectively at $\phi=10^{14}$n(1MeV)/cm^2 and $\phi=3\times10^{14}$e$^-$(7MeV)/cm^2 are the same. Assuming that the damage due to 1 MeV electrons is similar to that of 7 MeV ones (figure3), then $\phi=3\times10^{14}$e$^-$(1 MeV)/cm^2 is slightly equivalent to 1 Grad. The figure 4, shows that the effect of 1 Grad γ particles is similar to 10^{14}cm^{-2} neutron particles then 3×10^{14}cm^{-2} 1 MeV electron particles. These electrons are obtained in our samples by Compton effect process created by γ rays. So, it seems that the mechanism of creation of displacement damage γ rays in our samples is the scattering by Compton electron process. More work is needed to elucidate the radiation effects with γ particles at very high doses to determine exactly the introduction rate of displacement damages.

VI. CONCLUSION.

We have observed by PL measurement that irradiation with γ particles induces in n type GaAs a displacement damages. In the samples studied, gallium vacancy and silicon at the arsenic site were observed. We have purposed that the microscopic mechanism of creation of these displacement damages by γ particles is the recoil electrons created in our samples by Compton effect. The observation of these defects in our samples gives a microscopic explanation for the degradation of macroscopic properties observed in γ irradiated GaAs.

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