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6. AUTHOR(S)

Dr. Ralph J. Jaccodine
Dr. Donald R. Young

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lehigh University
Sherman Fairchild Laboratory
16A Memorial Drive East
Bethlehem, PA 18015

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The effect of germanium on the hot electron current of metal-oxide-semiconductor devices has been studied by avalanche electron injection from the silicon to silicon dioxide. Different doses of germanium ranging from 10^{12} to 10^{15} atoms/cm^2 are implanted into Si-SiO_2 interface. The "lucky" hot electron population is suppressed by germanium implantation. We have used the charge-voltage technique to measure the interface state density. The interface state density increase caused by Ge implantation is negligible if the dose is lower than 10^{14} Ge/cm^2.

We have also used different implantation energies to locate the Ge peak at different locations in the Si. We found that when the peak is at Si-SiO_2 interface, the hot electron population is the lowest.

Our results show that Ge implantation is a promising method to solve the hot carrier problem that has become important in submicrometer devices.

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An Extended Approach to Oxidations and Nitridations of Si and Ge_xSi_{1-x} Materials

Final Technical Report

Dr. Ralph J. Jaccodine
Dr. Donald R. Young

February 4, 1994

U.S. Army Research Office

DAAL03-92-G-0224

Lehigh University
Bethlehem, Pennsylvania 18015

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Final Technical Report

STATEMENT OF THE PROBLEM STUDIED

The effect of germanium on the hot electron current of metal-oxide-semiconductor devices has been studied by avalanche electron injection from the silicon to silicon dioxide. Different doses of germanium ranging from 10^{12} to 10^{15} atoms/cm^2 are implanted into Si-SiO_2 interface. The "lucky" hot electron population is suppressed by germanium implantation. We have used the charge-voltage technique to measure the interface state density. The interface state density increase caused by Ge implantation is negligible if the dose is lower than 10^{14} Ge/cm^2.

We have also used different implantation energies to locate the Ge peak at different locations in the Si. We found that when the peak is at Si-SiO_2 interface, the hot electron population is lowest.

SUMMARY OF THE MOST IMPORTANT RESULTS

The final effort in this project was extended to finish the work started previously by graduate student Ta-Cheng Lin. This effort had too much promise to be dropped at an incomplete stage. Our judgement is justified by the importance of his findings (see paper included)[1] and indeed should be further investigated in the future.

We have been intrigued by the work of Ng, Pai, Mansfield and Clarke[2] suggesting that the implantation of germanium into the Si-SiO_2 interface can significantly reduce the injection of hot electrons from the silicon into the silicon dioxide. They suggest that the Germanium reduces the hot electron population in the vicinity of the Si-SiO_2 barrier height without having a significant impact on the lower energy carriers that provide the current in an operating device. Since hot electron injection has become an increasingly important consideration for the ultra small devices used in contemporary silicon technology and because of the addition of the germanium implantation appears to be easily implemented on a production line, we have continued our effort to extend and verify this work.

As we described in the paper that is included, our results on MOS devices using avalanche injection techniques clearly support the results of Ng et al. A very large reduction in the hot electron population is observed which appears even for implanted germanium doses of $10^{12}/cm^2$. As the dose is increased, additional reductions are observed with no observable increase in the interface state density until the dose used is $10^{14}/cm^2$. It is well known that the presence of germanium in the SiO_2 provides electron traps with a relatively large trapping cross section. For this dose of $10^{14}/cm^2$, the volume concentration in the oxide is becoming large enough to provide enough traps within the tunneling distance of the interface to result in the interface states involved. So it is reasonable to suggest that the interface states are the result of electron tunneling into the germanium electron traps. However, lower concentrations can still provide a very useful result. This suggests a wide range in the applied dose can be considered. The results of this work are so encouraging that we are independently continuing it further to enable us to learn more about the physical mechanisms involved. This holds promise for future device technology.

REFERENCES

1. Ta-Cheng Lin and D. Young, Appl. Phys. Lett. **62** (26), 1993.
2. Ng, Pai, Mansfield, and Clarke, IEEE Electron Device Letters, 1990.

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

1. "Effect of Germanium Implantation on Metal-Oxide-Semiconductor Avalanche Injection," Ta-Cheng Lin and Donald R. Young, Appl. Phys. Lett. **62** (26), 1993.

REPORT OF INVENTIONS

No inventions are reported for the time period of this report.

BIOGRAPHIES

Dr. Ralph J. Jaccodine

Director, Sherman Fairchild Center for Solid State Studies

Education

1947	B.S.	U.S. Naval Academy
1951	M.S.	Physics, Steven Institute of Technology
1957	Ph.D.	Physics, Notre Dame University

Positions

Bell Telephone Laboratories (1958-1981)

1959-61	Member of Technical Staff
1961-68	Supervisor on wide range of crystal growth related studies
1972-78	Department Head of MOS Technology
1978-81	Department Head of Bipolar Technology
1981-	Fairchild Professor of Solid State Materials, Lehigh University

Research Activity

Stacking faults and distortion behavior
Integrated circuits and devices
Solid state diffusion
Oxygen precipitation
Imperfection studies
IEEE Gel Task Force
Bipolar technology
Ion implantation
MOS technology
Director, SRC Packaging Program

Society Membership

IEEE (senior member)
Electrochemical Society
Sigma Xi

Dr. Donald R. Young

Education

1942 B.S.	Utah State Major-Physics; Minor-Mathematics
1949 Ph.D.	Massachusetts Institute of Technology Major-Physics; Minor-Mathematics

Positions

1942-45	Massachusetts Institute of Technology Radiation Laboratory
1945-49	Massachusetts Institute of Technology Laboratory for Insulation Research
1949-86	International Business Machines
1972-73	Sabbatical leave as visiting Mackay Lecturer Electrical Engineering Department University of California
1980-81	Sabbatical leave at Institut fur Halbleitertechnik Technische Hochschule, Aachen, Federal Republic of Germany. U.S. Senior Scientist Award, Alexander von Humboldt Foundation
1982-86	Adjunct Professor, Lehigh University, Bethlehem, PA (with exception of 1984)
1986-	Professor, Lehigh University

Personal Recognition

Fellow American Physical Society, Fellow IEEE
U.S. Representative on Committee on MIS Systems
A. von Humboldt Senior Scientist Award 1980
Chairman, 1982 Gordon Conference on MIS Systems
Two Outstanding Contribution Awards IBM

APPENDIX

"Effect of Germanium Implantation on Metal-Oxide-Semiconductor Avalanche Injection," Ta-Cheng Lin and Donald R. Young, Appl. Phys. Lett. **62** (26), 1993.

Effect of germanium implantation on metal-oxide-semiconductor avalanche injection

Ta-Cheng Lin and Donald R. Young
Sherman Fairchild Center, Lehigh University, Bethlehem, Pennsylvania 18015

(Received 1 March 1993; accepted for publication 15 April 1993)

The effect of germanium on the hot electron current of a metal-oxide-semiconductor device has been studied by avalanche electron injection from the silicon to the silicon dioxide. Different doses of germanium ranging from 10^{12} to 10^{15} atoms/cm^2 are implanted into the Si-SiO$_2$ interface. The "lucky" hot electron population is suppressed by the germanium implantation. We have used the charge-voltage technique to measure the interface state density. The interface state density increase caused by the Ge implantation is negligible if the dose is lower than 10^{14} Ge/cm^2. Our results show that the Ge implantation is a promising method to solve the hot carrier problem that has become important in submicrometer devices.

One of the physical phenomena in silicon metal-oxide-semiconductor field-effect-transistor (MOSFET) structures that is becoming increasingly important for ultrasmall devices is the emission of hot electrons from the silicon substrate into the silicon dioxide insulating layer. The trapping of the hot carriers in the silicon dioxide induces device degradation and instability. Several approaches[1–4] have been proposed to circumvent this problem. One method recently presented by Ng *et al.*[5] is to introduce neutral atoms in the MOSFET channel region to suppress or eliminate the hot carrier population. They observed a decrease in the degradation rate of MOSFETs resulting from the presence of Ge in the channel. They also observed that the device operating characteristics are not degraded and they claimed that the germanium introduces an additional scattering mechanism for the lucky hot electrons.

In this work, we investigate the effect of germanium on the hot electron injection using MOS devices. Different doses of germanium are implanted into the Si-SiO$_2$ interface of MOS structures. We use the avalanche injection technique[6] to generate hot electrons in the substrate. The injection current and the corresponding peak avalanche voltage are monitored for each sample. Our observations indicate a reduction in the injected current resulting from the presence of germanium. The experimental results and discussion will be presented later. We also use the charge-voltage (Q-V) technique[7] to investigate the effect of Ge on the interface state density for each sample.

p-type, 0.1–0.2 Ω cm, ⟨100⟩ wafers are used as a substrate. All wafers are RCA cleaned before oxidation. The oxide is grown in a dry oxidation furnace at 1000 °C for 50 min. After oxidation, one half of each wafer is implanted with germanium. The doses are 10^{12}, 10^{13}, 10^{14}, and 10^{15} atoms/cm^2 at an energy of 95 keV. The other nonimplanted half is the control sample to be compared with the implanted half. After implantation, samples are annealed for 30 min in a N$_2$ ambient at 950 °C to eliminate implantation damage. Aluminum gates are deposited on top of the wafers using evaporator. The gate area of 0.01 cm^2 is defined by photolithography. Finally, the devices receive a 400 °C, 30 min post-metallized annealing in a forming gas (20% H$_2$, 80% N$_2$ mixture).

The densities of the interface traps for each sample were analyzed by the Q-V technique.[7] The effect of germanium implantation on the interface state densities will be given later.

Avalanche injection has been described respectively by Young and Nicollian[8,9] in their previous papers as a means to induce a current flow in the oxide. Figure 1 shows the band diagram of the MOS structure under avalanche condition. The MOS capacitor is driven to deep depletion and carriers in the silicon substrate are accelerated by the applied electric field. These hot carriers have sufficient energy for impact ionization to occur. Thus, electron hole pairs are created in the depletion layer. The lucky hot electrons that have enough energy to surmount the interfacial barrier enter the SiO$_2$ to produce an electron current. Thus, by observing the injection current, we can study the hot electron effect in MOS devices. In this work, the injection current and the corresponding applied voltage are carefully

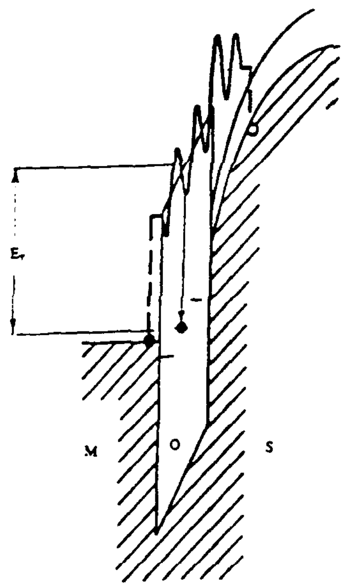

FIG. 1. The energy band diagram of a p-type MOS capacitor for semiconductor avalanche emission under large positive bias.

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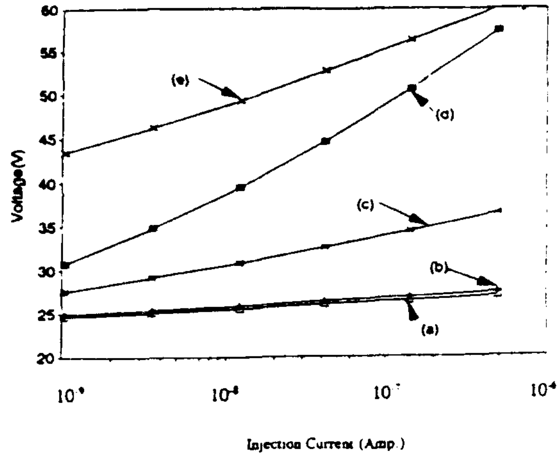

FIG. 2. Avalanche injection voltage vs current for all samples. Electrons were injected from silicon substrate. (a) Control, (b) 10^{12} Ge/cm^2, (c) 10^{13} Ge/cm^2, (d) 10^{14} Ge/cm^2, and (e) 10^{15} Ge/cm^2.

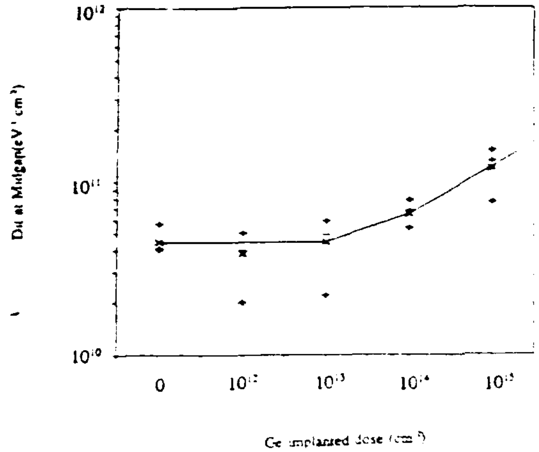

FIG. 3. Ge implanted dose dependence of interface state density at midgap. For each sample, "+"s are the measured D_{it}, "×" is the average D_{it}.

recorded for each sample. The result will be presented later.

Figure 2 shows the voltage versus injection current curves for each sample. We observed the voltage required to produce a given current increases for the Ge implanted samples. The 10^{15} Ge/cm^2 sample has the highest voltage increase and the voltage goes down as ne Ge concentration is decreased. When the dose is 10^{12} Ge/cm^2, the germanium has almost no effect on the voltage. The increase in avalanche voltage required for a given current demonstrates a decrease in the injection current for the same voltage. Based on the above observation, we conclude that this is a large reduction in the hot electron population in the silicon substrate as a result of the germanium. The reduction in hot electron population is due to additional scattering mechanisms. The added scattering may be caused by the larger atom size of Ge or by a disturbance of the band structure.

The interface state densities at midgap of all samples are shown in Fig. 3. It is evident that D_{it} does not increase until the germanium dose is higher than 10^{14} Ge/cm^2. The increase in the interface state density was probably caused by the implantation damage. This result suggest that we keep the dose below 10^{14} Ge/cm^2 to avoid the D_{it} increase.

In this work, we have observed a reduction in the hot electron population in a Si substrate as a result of germanium implantation into the interfacial region. This reduction in hot electron population would lower the degradation rate of MOSFETs. Our results agree with Ng's experiment. In the range of our study, the more Ge we have in the interface the lower the hot electron population. On the other hand, when the germanium dose is higher than 10^{14} Ge/cm^2, the interface state will increase. So the optimistic dose, which reduces the hot electron population without increasing the interface state density, in this study is 10^{14} Ge/cm^2.

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