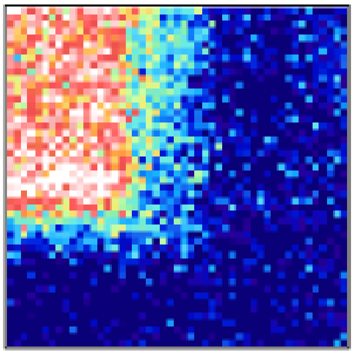
Final Report		
Ente Consiglio Nazionale delle Ricerche Istituto di Fotonica e Nanotecnologie	Tipo di documento Rapporto Tecnico	Classificazione Uso interno CNR
Riferimento	Numero documento 1	Pagine 11
Data 26/11/2015	Revisione Enrico Prati	

Final Report

Short Term Mobility 2015

Process and pre-characterization of erbium doped silicon transistors



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Indice delle revisioni			
Revisione numero	Revisionato da	Motivazione	Data revisione

Indice degli acronimi	
SEM	Scanning Electron Microscope
RTA	Rapid Thermal Annealing

Definizioni	

Documenti di Riferimento

Questo Rapporto Finale fa riferimento ad articolo scientifici pubblicati dagli Autori:

[1] E. Prati *et al.*, *Anderson–Mott transition in arrays of a few dopant atoms in a silicon transistor*, Nature Nanotechnology (2012)

SCOPO DEL DOCUMENTO

Questo documento costituisce il Rapporto Finale dell'attività svolta dal Dr. Enrico Prati dal 30 Ottobre 2015 al 19 Novembre 2015 presso la Waseda University Tokyo nel contesto dello Short Term Mobility 2015 del CNR. Esso riporta i risultati relativi al processo e alla precaratterizzazione elettrica di transistor di silicio il cui canale è impiantato di atomi di erbio, un tipo di atomo rilevante per l'integrazione della fotonica nel silicio per le sue proprietà ottiche a 1540 nm.

Indice

1. Introduction

The preparation of the ErO implanted devices was carried at the Tanii's Lab at Waseda University. The objective was to implant Er and O in the channel of backgated transistors, where electroluminescence may be achieved at 1530 nm. In order to take advantage of the stay, the determination of the density of Er, planned to be carried during the first week in the proposal, was anticipated before the start of the stay in Waseda. This decision allowed to save time during the stay in Japan and to employ it to develop the process in the cleanroom more effectively. According to photoluminescence measurement carried before the stay on bulk silicon substrates (see Figure in the Cover, in collaboration with of M. Celebrano, Dipartimento di Fisica Politecnico di Milano), we opted to implant at least 4.5 10^{12} cm^{-2} atoms of Er while O was implanted with a density of 2.5 10^{13} cm^{-2}. We therefore opted to implant Er atoms at such dose and at a 9 times higher dose of 3 10^{13} cm^{-2}.

2. Preparation of Er O co-implantation

First, we needed to decide whether a resist mask was required for alignment of the devices, so we scheduled and performed first a research on the the secondary electron emission imaging. The sample was loaded by a probe entering the implantation chamber with vacuum of 8 10-5 Pa. The ErSiAu metal becomes liquid at a temperature of 650 C. and emission starts. A current of 3 A was used for raising the temperature, by steps of 0.2 A. Extractor voltage was set at -2.66 kV with -4 uA current. Acceleration is next raised from 0 to 10kV. Next extractor is moved to -2.93 kV so emission is 4.4 uA. To let the beam stable, -3.1 kV was achieved together with 5.4 uA emission. The image of secondary electrons appeared as a byproduct of alloy hitting the devices. After applying magnetic tips, the only Er is used, by confirming the visibility of the bright squares markers at the crosses between devices. Device could be identified so implantation was possible with no need of additional mask, which would delay and increase complexity of the process.

3. Preliminary etching and capping tests

Etching. In order to implant Er through the thinnest possible oxide, as the sample channel is capped by 15 nm thermal oxide, the device is dip for 90 s in BHF. IV curves are tracked before and after etching. After 30 minutes the native oxide is formed and all the devices still correctly operate with a small change in terms of small decrease of threshold voltage and reduction of conductivity at high gate voltage.

Capping. Subsequently, the effect of the resist was tested as temporary capping, needed for O implantation. After 5 min at 105 C, a 2 drops of HDMS for single layer polymer were deposited and spinned and next 2 drops PMMA was spinned. PMMA was diluted 10:2 in ZEP-A. 10 seconds to 5000 rpm and spin 60 seconds; to 550 rpm in 5 seconds and next 3300 rpm for 40 s. After baking 90 s at 180 C the removal procedure was applied.
Tetrehydrofuran is used for removing in sonic for 1 m, for 3 times at room temperature. Acetone was used for cleaning. 60 s for 3 times in sonics, and next clean by water. The samples were tested after the process and proved safely operating.

4. Er and O implantation

Erbium Implantation: Four batches of samples including 1um x 1 um, 1 um x 2 um, 1 um x 5 um, 1 um x 10 um and 500 nm x 10 um have been implanted by using Er concentration of 4.5 10^{12} cm^{-2} (density **A**, two batches) and 3 10^{13} cm^{-2} (density **B**, two batches). The ion dose was previously characterized and normalized so, according to available flux, the exposition was 2m30s for the first and 2m for the second by focusing on 1/9 of the previous surface. We opted not to test implanted devices before annealing as the presence of defects may increase the probability of breakdown if large voltage of volts is applied.

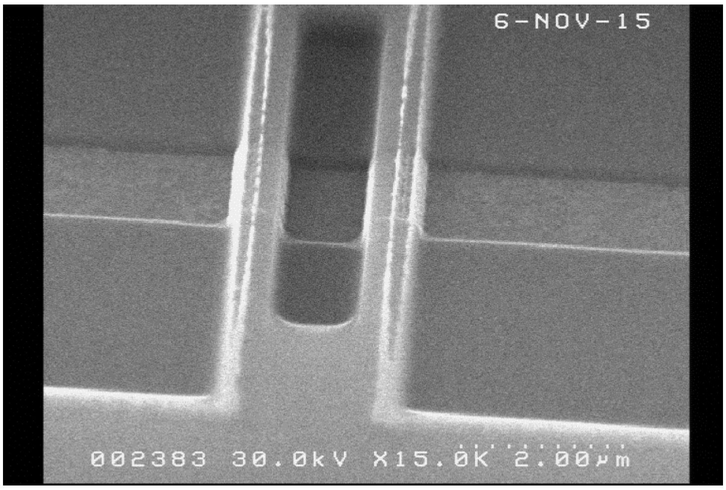

Figure 1. SEM image of the transistor. The aperture on the channel is visible.

Oxigen implantation: After the implantation of Er, the implantation of O has been carried.
Such process is not difficult in principle, but as the O has very different implantation profile with respect of the Er, an appropriate capping resist was needed before implantation. We therefore observed with bird view SEM imaging the height of the resist deposited at the previous step and we determined the need of reducing thickness by additional process step. We took reference from standard silicon with same resist capping process. To determine the

height of resist after etching we immersed in PMMA developer for time windows of 5 minutes and observed with microscope the color change to confirm each etching (started from purple in corner and blue, next step purple in corners and yellow). Each step was expected to reduce about 15 nm, later confirmed by SEM. We opted to etch the devices for 10 minutes and later time was verified by the SEM image.
The SEM image showed an unsatisfactory profile, so we decided to modify the process.
We repeated the process to thin the resist required for oxigen implantation. The dilution of the resist was changed to 5:7 and spinning speed increased of 5000 rpm. Next, SEM imaging was carried and lower profile of resist was discovered still 100-140 nm (**Figure 1**). The observation suggested to adjust the resist preparation to a dilution of 1:2 and spinning of 5000 rpm for 40 s.

Figure 2. Operation of loading the sample in the oxigen plasma.

An additional test was performed, to verify that transistors, after removal of resist by etching, were still normally operating after O plasma etching for 5 minutes at 200 W in a Yamato Plasma Reactor 301 (**Figure 2**). First, we performed the plasma etching. Next, we recorded the IV of all the devices, by discovering a higher mobility after plasma etching, which is compatible with the removal of surface impurities which affect the transport, being the top oxide not covered by a gate. 100% of devices was behaving correctly after plasma etching.
The transistors were therefore processed with such final process recipe for oxygen implantation. The devices were loaded into the oxigen implanter ULVAC UP-250. The dose is opted for being the same as the sample 20 which is 2.5 10^{13} cm^{-2}. After 25 minutes, the dose was achieved. All the transistors implanted at the two Er doses were implanted at the same oxigen flux. Next, 5 minute of standard oxigen plasma were applied with output power of 200 W in a Yamato Plasma Reactor 301. Next, cleaning was completed in liquid. First test was done on the dummy device with THF for 1 m, again 1 m and next acetone 30 s. Finally it was cleaned with pure water. After confirming successful operation on the dummy sample with microscope, the identical recipe was repeated on the implanted sample.

5. Test and annealing

In order to assess the annealing of the implanted sample, we performed IV curves after the resist removal and all the devices displayed correct behaviour of a transistor. Next, we applied annealing to the dummy sample by using ULVAC MILA3000 for 30 minutes at 900 C after pumping vacuum for 5 minutes and ramp to 900 C in 90 s. Ramp back is also 90 s after the 30 m of annealing.

All the devices were tested after annealing with 100% success, revealing that 30 m annealing did not damage contacts. Sample C10 which has a 100 nm channel was tested as reference to check diffusion of dopants from contacts in the channel, and no diffusion effects were observed. The Er and O implanted device was annealed with the same procedure, consisting of ULVAC MILA3000 for 30 minutes at 900 C after pumping vacuum for 5 minutes and ramp to 900 C in 90 s. Ramp back is also 90 s after the 30 m of annealing.

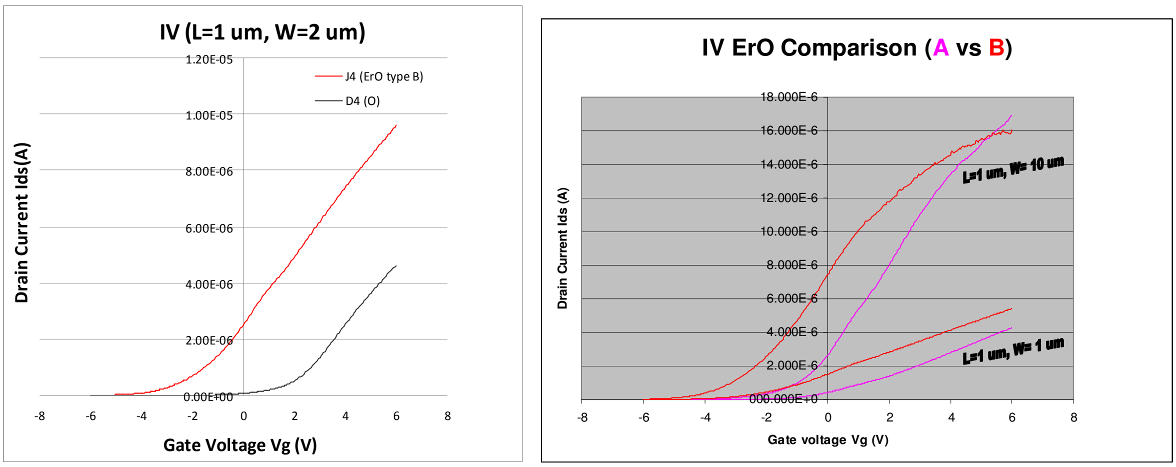

Figure 3. Electrical characterization of representative conditions. Left: the O implanted device shows ordinary transport not varied from the not-implanted transistor, while the ErO implanted device (at the density B) has a lower threshold voltage associate to an impurity band. Right: comparison between the Er implantation density A and B).

6. Electrical pre-characterization

All the devices were tested after annealing. The backgate voltage was scanned between -6 and 6 V, while bias Vds was set to 100 mV. A set of samples diffused with O were not diffused by Erbium, both short (C10, 100 nm) and long (D4 and D5, 1000 nm) versions, displaying no significant changes with respect from not diffused devices. Therefore we could conclude that diffusion of dopant from contacts during annealing does not affect transport not only before O implantation, but also combined with O. On the contrary, Er implanted device exhibits a sub threshold transport which is determined by the implantation of Er (density **A**), which further increase when the dose is increased by a factor of 9 at the density **B** (**Figure 3**). Consequently, we could identify the effect on the transport of the Er implantation.

According to literature, the annealing of Si:ErO at 900 C like the case of our transistors determines the formation of a defect which lies at Ec - 150 meV, which is partially ionized by thermal excitations at 300 K, while other defects normally present by annealing at lower temperature disappear. Such defect is expected to form an impurity band which is not generally exploited in diode structures, while the transistor device, thanks to the control of the back gate voltage, may explore. We confirmed the existence of such an impurity band by the sub-threshold transport of the devices.

7. Additional optical tests

It is worth to mention that we also attempted photoluminescence measurements similar to those carried in Italy at Polimi Dipartimento di Fisica, where a single photon counter was used at room temperature. In Waseda a standard equipment was available. The device 24L was implanted O 2.5 10^{13} cm^{-2} in bulk, while 24R 1 10^{14} cm^{-2} so we attempted to measure both with a standard equipment available at the Lab of Prof. Utaka. The beam spot is of about 100 um at the fiber interface, while the beam is larger so multiple dots may be accessed. The position was set by a microcontrolled stage. The excitation wavelength was of 670 nm. As expected, no PL signal was observed as the area is too small so the measurements will be attempted again in Milan with single photon counters.

8. Possible exploitations

In order to exploit Si:ErO doped transistors, a number of electrical and hybrid optoelectronic characertizations have been conceived during the stay to be carried in Milan. Three different conditions may be explored by using the transistor. First, (a) by setting the Vg where the current is off. There, the ground states of the Er defects are empty. In the second, (b) the gate voltage Vg is set at the bottom of the impurity band The defects are partially filled, which determines that the only excess charge in the semiconductor is localized, which determines the special condition of having only localized and not free electrons like those in the conduction band, which are known to have severe effects on the suppression of exciton lifetime. Finally, the third condition (c) is with the Vg in the impurity band above 0 V, which transfers the electrons from the top interface to the bottom interface, where Si:ErO density is expected to be much lower and conduction band transport sets in.

9. Conclusions

The work can be summarized with two main conclusions:

1) The vertical alignment of the implantation depth of Er and O for the back-gated transistors respectively was successfully achieved thanks to a fabrication process defined during the stay, with no damage for the operability the transistors

2) The Er implanted devices exhibit a lower threshold voltage which appears as an impurity band extending the DoS in the band gap. It is compatible with the formation of a defect at -150 meV constituted by the cluster ErO_6, as expected after annealing at 900 C.

To conclude, the **implantation of Er in silicon transistors proved successful** and full characterization will be carried in CNR in Milan according to the plan.