Project Acronym : **AFSiD**

Atomic **F**unctionalities in **Si**licon **D**evices

Project no. 214989

Nano ICT project

Deliverable D1.3 :
Report on single and coupled dopant device with two gates, deep dopant devices

Due date: Month 42

Delivery date: Month 42

Estimated manpower indicated in the grant agreement: 26 MM

Effective effort: 29 MM

The AFSID deliverable 1.3 entitled "Report on single and coupled dopant device with two gates, deep dopant devices" focuses on the investigation of the most involved implementations of single dopant transistors (SATs). That includes three types of multi-gate devices and devices with donors with a large ionization energy. The former are aimed at the achievement of higher, i.e. complex, functionality of the SATs. The latter is aimed at the investigation of possible higher operation temperatures of SATs. With the AFSID batch II devices great progress was achieved and D1.3 was delivered in month 42 as outlined below. The initial aim was to deliver D1.3 at the end of the project at month 36 but this was shifted with the extension of the project granted after the 2nd review to month 42. The plan was to use 26MM on this deliverable which is close to the 29MM actually spend by partners CEA, Mel, and TUD.

Single dopant device with two gates

The AFSID results with single dopant and two gate devices are based on single gate devices with a back gate and devices with a split top gate, i.e.: double gates on the side of the transistor channel.

Partner CEA did a systematic investigation of dopant variability by using the top gate and back-gate of a single gate device (left panel of Fig. 1). The back-gate is realized by applying a voltage between source-drain and the handling wafer of the silicon on insulator (SOI) substrate. An undoped device shows an onset of conduction due to the back or front gate close to the theoretical threshold voltage. The coupling of the two is different due to the difference in capacitance but otherwise the behavior is identical. The source-drain current as function of the front and back gate voltage of a doped sample shows a much richer structure. Charging events in the body of the SOI are observed. Furthermore, few isolated lines appear below the theoretical threshold due to the ionization of single phosphor donors in the body.

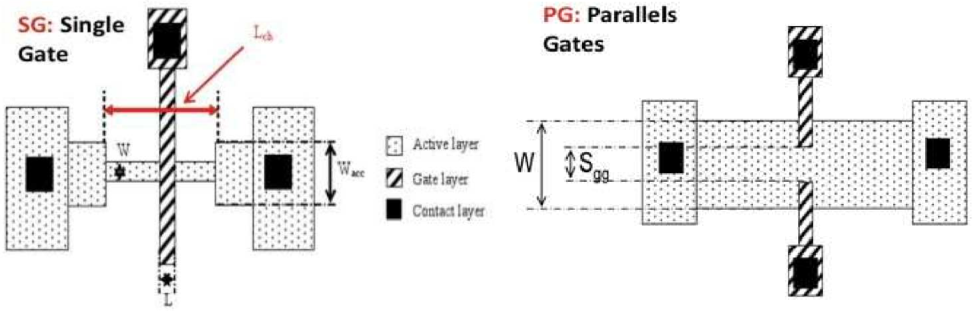

Fig. 1: (left) single gate device where the backgate, i.e. the handling wafer, is used in combination with the top gate to invert the device. (right) Split-gate device used for single ion implantation and transport through a deterministically doped device.

Partners Mel and TUD investigated devices with "split-gate" geometry, i.e.: devices that have two gates that almost touch each other on the channel (right panel of Fig. 1). The aim was to electrostatically control the potential of the channel and still be able to implant a dopant into that same channel. This was a challenge since the distance between the two gates needs to be small such that an angled LDD or/and HDD implants do not reach the channel between the two gates when the source and drain are doped. Furthermore no backend processing could be used. In a sequence of transport evaluation at low temperature, followed by annealing and single ion implantation, AFSID demonstrated that it is possible to deterministically dope such a device and observe the dopant in the channel by a change in threshold at room temperature and in quantum transport at low temperature.

Coupled dopant device with two gates

Partner CEA investigated transport through a coupled donor in a dual gate device as shown in Fig. 2. Here the two gates are next to each other across the channel. In such a device with P background doping at 10^{18}cm^{-3} it was possible to observe sub-threshold transport through two dopants in series in the constriction defined by the two gates. The electrons tunnel from the source into the first dopant controlled by the left gate and then to the next dopant that is controlled by the right gate and then to the drain. There is cross coupling between the gates, but the chemical potential of each dopant can be controlled independently. Besides tunneling though the two ground states of the dopants, CEA partner also demonstrated transport through the ground state of one dopant and the excited state of the other. The energy splitting between the ground state and the excited state was measured to be 10 meV close to the bulk value of 11.6meV. The discrepancy is well accounted by simulations if the donor is located 3 nm above the buried Si/SiO2 interface. The latter is an interesting observation since in this device behaves very much like a dopant atom in the bulk, i.e. exhibits a very large valley splitting.

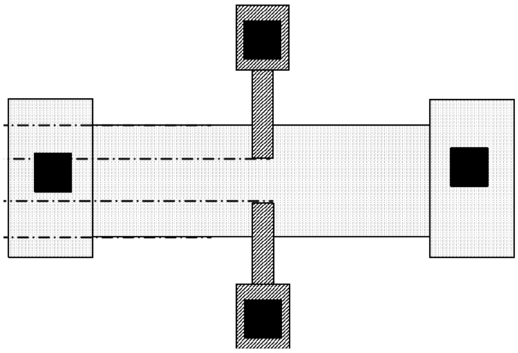

Fig. 2: Double gate device with two face-to-face gates over the same channel Width=70nm gate Length=40nm, spacing between gates Sgg = 30nm

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Deep dopants

The interest in deep dopants is based on the possibility to enhance the operation temperature of SATs. In a MOS SET the charging energy is defined by the device size. In contrast, the charging energy of a SAT is given by the atomic species that binds the electron. Shallow impurities have a charging energy of about 40-50meV and charge quantization becomes dominant below 100K. In AFSID we investigated devices with Se dopants, which have a charging energy that is about 6 times higher than that of P or As.

Partners TUD and CEA investigated the variability of Se doped devices based on a large ensemble measured at room temperature. Even at a doping concentrations of 2 10^{18} /cm^3 only a slightly lower threshold was observed in comparison to an undoped device. The threshold distribution was also similar to an undoped device. This indicates that the doping-induced variability is not present in these devices in contrast to identical devices with the same concentration of P. Low temperature transport experiments on 20nm Se doped devices did not yield a localized state consistent with a deep dopant. A model of the tunneling probability was developed based on wave-function overlap between contacts and the localized state of the dopant. In contrast to a simple square barrier model, which was generally believed to be adequate, this model predicts considerably higher coupling strengths. The model was confirmed by experiments on AFSID devices with the shallow impurities. For Se donors this model predicts that adequate coupling requires channel lengths of 10nm or less. The shortest working devices in AFSID have a channel length of 20 nm. Based on this analysis only the combined statistical event of finding a Se atom in the middle of a 10 nm channel of a nominally 20 nm device would lead to Se based transport. It was concluded that only devices with a 10 nm channel length and low variability would be suitable for deep donors.