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Magnetoconductivity of Hubbard bands induced in silicon MOSFETs

T. Ferrus*, R. George, C.H.W. Barnes, N. Lumpkin, D.J. Paul, M. Pepper

Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, CB3 0HE, Cambridge, UK

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Abstract

Sodium impurities are diffused electrically to the oxide-semiconductor interface of a silicon MOSFET to create an impurity band. At low temperature and at low electron density, the band is split into an upper and a lower sections under the influence of Coulomb interactions. We used magnetoconductivity measurements to provide evidence for the existence of Hubbard bands and determine the nature of the states in each band.

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1. Introduction

In the early 1970s a substantial effort was put into the study of the effect of impurities in silicon MOSFETs. The main reason for this was to understand the origin of the instabilities in field effect transistors and the unpredictable changes in the threshold voltages. These studies contributed to improve the performance of a new generation of silicon-based chips for computer applications and their reliability. In fact, the presence of impurities or defects in the silicon oxide leads to an inhomogeneity in the electron distribution at the Si–SiO_2 interface and traps electrons. The most common impurities are alkali metals like lithium, potassium or sodium. These trap states give rise to the formation of an impurity band below the conduction band. This effect was first observed by Fang, Hartstein and Pepper [1–3] for high impurity concentrations ($>1\times10^{12}\,cm^{-2}$). A consequence of the existence of such an impurity band is that the onset voltage for conduction in oxide-doped MOSFETs is also shifted and the electron mobility substantially decreased. The impurity band produced by such a doping can be described by tight-binding models for high impurity density [4] whereas Mott–Hubbard models [5] need to be used for the low concentrations for which Coulomb interaction plays a defining role. Given single valency atoms like sodium, it would be expected that the electronic states in the band are made of single trapped electrons. Under the influence of electron–electron interactions, it has been suggested, however, that a stable state with two bound electrons would exist and would be characterized by a long lifetime (D_- state) [6,7]. The band formed by the D_- states is referred as the upper Hubbard band (UHB) and the one formed with neutral states as the lower Hubbard band (LHB). The question of the existence of Hubbard bands in silicon MOSFETs has been put forward by Mott nearly 30 years ago to explain the magnetoconductivity of short disordered MOSFETs but the bands were never directly observed in experiments [8]. The study of Hubbard bands in semiconductors has regained some attention since the end of the 1990's with the development of quantum information and quantum computation [9]. Following the difficulty in reading out directly the value of the spin in architectures developed in agreement with the Kane model, a spin to charge conversion was proposed. In this approach, a stable D_- state is used to read out the result of the quantum operations. Some optical studies have previously been carried out in Mott–Hubbard insulators like Sr_2CuO_3 [10] or boron-doped diamond [11] but no

*Corresponding author.
E-mail address: taf25@cam.ac.uk (T. Ferrus).

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direct conductivity measurement has been performed so far. In the present paper, we have used magnetoconductivity measurement to provide direct evidence of the presence of Hubbard bands in a sodium-doped silicon MOSFET. We also describe the electronic configuration of the obtained D_- state by distinguishing between $1s^2$, 1s2s and 1s2p states.

2. Experiment

All measurements were performed on silicon MOSFETs. Such devices have been widely used because of the ability to continuously vary the electron density and the Fermi energy by use of a metal gate. The geometry of the device was chosen to be circular (Corbino geometry) to avoid leakage current paths around the source and drain contacts. The devices were fabricated using a high resistivity ($10^4\,\Omega$cm) (1 0 0) p-silicon wafer to minimize, as much as possible, the scattering with boron acceptor impurities, especially close to the silicon-oxide interface. A 35 nm thick gate thermal oxide was grown at 950 °C in a dry, chlorine-free oxygen atmosphere. The sidewalls of the oxide were protected by thick insulating LOCOS (local oxidation of silicon). The effective gate length of the Corbino MOSFETs was 1 μm and the diameter of the interior contact was 110 μm. Contacts were realized by implanting phosphorous at high dose and sputtering aluminium. The contact resistivity was measured to be 3.5 and $2.3\,\Omega\,\mathrm{cm}^{-1}$ at nitrogen and helium temperatures, respectively, and the sheet resistance was 6.3 and $5.9\,\Omega\,\square^{-1}$ for the same temperatures. Sodium ions were introduced onto the oxide surface by immersing the device in a 10^{-7} N solution ($\sim 6.4\times10^{11}\,\mathrm{cm}^{-2}$) of high-purity sodium chloride in deionized water. The surface of the chip was then dried with nitrogen gas and an aluminium gate subsequently evaporated. The application of a positive gate voltage (+4 V at 65 °C for 10 min) causes the sodium ions to drift towards the Si–SiO_2 interface while the application of −4 V DC in the same conditions removes the ions from the interface. The ions are frozen at their position once the device temperature becomes lower than approximately 150 K (Fig. 1). Standard low-noise lock-in techniques with an amplifier gain of 10^8 V/A were used to measure the source to drain conductivity. An AC excitation of amplitude $V_{AC} = 15\,\mu$V and a frequency of 11 Hz were chosen. The DC offset of the amplifier was suppressed using an appropriate blocking capacitor. The gate voltage was controlled by a high resolution digital to analog converter and the temperature measured by a calibrated germanium thermometer. The magnetic field was produced by an Oxford 12 T superconducting magnet and applied perpendicular to the Si–SiO_2 interface.

Several devices were processed identically and gave results that lead to identical conclusions although we noticed some variation in the relative position and width of the impurity bands, as well as in the conductivity values. From the difference in the threshold voltage at 77 K, we obtained an effective ion density of $\sim 3.7\times10^{11}\,\mathrm{cm}^{-2}$ at the interface indicating that only 60% of the ions drifted to the interface. We also fabricated a number of control devices that were not exposed to sodium contamination and were used for comparison. The following results are presented for a specific device that was chosen for its high reproducibility in time as well as for its high signal-to-noise ratio.

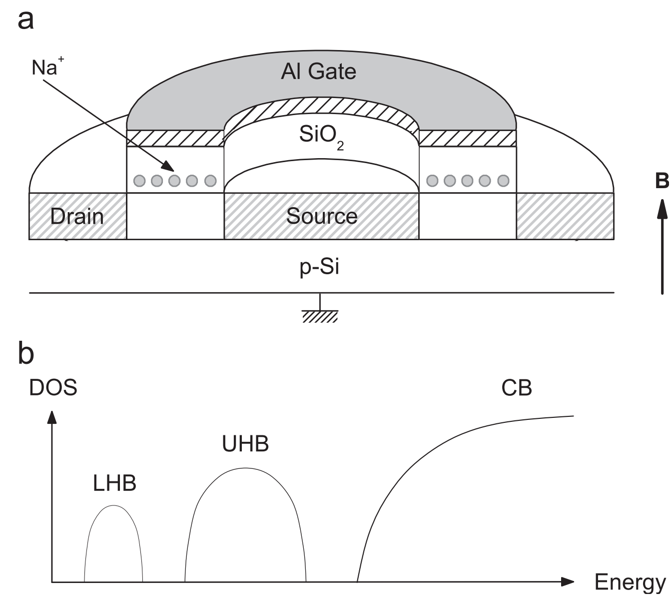

Fig. 1. (a) Cross-section view of a corbino MOSFET used in the experiment when the sodium ions are close to the Si–SiO_2 interface; (b) schematic diagram of the density of states (DOS) for the present device, with a low energy (LHB) and a high energy (UHB) impurity band separated by a gap to the conduction band (CB).

3. Results and discussion

Fig. 2a represents the source-drain conductivity obtained at different values of the magnetic field. The dependence of conductivity on temperature for the same device in the hopping regime showed the presence of two groups of peaks clustered around $V_g = -2$ and -0.5 V. These were attributed to a split impurity band due to the presence of sodium impurities at the Si–SiO_2 interface [12]. Arguments in favour of Hubbard bands were provided by studying the variation of conductivity at higher temperature, where activation mechanisms determine the behaviour [13].

3.1. Negative magnetoconductivity

The magnetoconductivity was found to be negative for the whole range of gate voltages studied. This is expected and was already observed in localized systems [14–16] (Fig. 2b). The variation with magnetic field is well described by $\ln\sigma \sim -\alpha B^2$ even at fields up to 5 T, where α is gate voltage dependent. This behaviour is often attributed to an orbital compression of the donor