Fabrication and Characterization of Microfluidic Field Effect Transistor on Silicon Substrate

by

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LIST OF ABBREVIATIONS

Al = Aluminum

BJT = Bipolar Junction Transistor
BOE = Buffered Oxide Etch
CTA = Conventional Thermal Annealing
DIW = De-ionized Water
DNA = Deoxyribonucleic Acid
EDL = Electrical Double Layer
FET = Field Effect Transistor
HPM = High Power Microscope
ICP-RIE = Inductive Coupled Plasma-Reactive Ion Etching
KITE = Keithley Interactive Test Environment
KOH = Potassium Hydroxide
MEMS = Microelectromechanical Systems
MOSFET = Metal Oxide Semiconductor Field Effect Transistor
MOSol = Metal-oxide-solution
NMOS = N-channel Metal Oxide Semiconductor
OFM = Oxidation Furnace Module
PECVD = Plasma Enhancement Chemical Vapour Deposition
PR = Photoresist
PVD = Physical Vapour Deposition
RCA = Radio Corporation of America
SC = Standard Cleaning
SEM = Scanning Electron Microscope
Si = Silicon
SiO_2 = Silicon dioxide
SMU = Source Monitor Units
SOG = Spin On Glass
SPA = Semiconductor Parametric Analyzer
UV = Ultraviolet
WCM = Wet Cleaning Module
µTAS = Miniaturized Total Chemical Analysis System
+ve = Positive
-ve = Negative

LIST OF SYMBOLS

Quantity	**Symbol**	**Unit**
Drain current	I_D	Ampere (A)
Drain voltage	V_{DS}	Volts (V)
Gate voltage	V_G	Volts (V)
Load resistance	R_L	Ohm (**Ω)**
Load resistance voltage	V_L	Volts (V)
Sheet resistance	R_s	ohms per square (**Ω/□)**

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FABRIKASI DAN PENCIRIAN TRANSISTOR KESAN MEDAN BENDALIR MIKRO DI ATAS SUBSTRAT SILIKON

ABSTRAK

Pembinaan transistor kesan medan pengaliran bendalir mikro berasaskan silicon telah dijalankan. Objektif utama kajian ini dijalankan adalah untuk mempersembahkan daripada konsep, rekabentuk transistor kesan medan pengaliran bendalir mikro dan menghasilkan aliran proses yang berkaitan dalam fabrikasi transistor kesan medan bendalir mikro di atas kepingan silicon, yang akhirnya akan diperincikan menggunakan ujian-ujian yang bersesuaian. Maka, fabrikasi di atas silikon jenis p-<100> bersaiz 4 inci melalui proses fotolitografi, hakisan secara kimia, pengoksidaan termal, penyesaran dan pelogaman dengan focus khususnya ke atas laluan konduksi bendalir telah dijalankan. Tiga peringkat topeng foto telah direkabentuk menggunakan perisian AUTO-CAD dan dicetak krom di atas kaca jenis soda-kapur. Struktur asas peranti ini telah diadaptasi daripada struktur MOSFET sedia ada dan telah diolah untuk menggabungkan laluan bendalir di dalam operasinya. Oleh itu, tiada perubahan dari segi fungsi tetapi laluan konduksi utama diganti dengan bendalir, dan bukannya semikonduktor yang telah didopkan. Dua tangki dihubungkan melalui satu laluan bendalir dengan setiap satu kawasan punca dan saliran yang telah didopkan diletakkan di kedua-dua bahagian yang bertentangan dengan laluan bendalir untuk mengurangkan konduksi terhadap substrat. Kedua-duanya diletakkan jauh antara satu sama lain bagi meminimakan pengaliran elektron melalui laluan bendalir bilamana aliran tersebut tidak diisi dengan cecair. Lebar aliran telah ditetapkan kepada lima saiz, iaitu 5 μm, 20 μm, 50 μm, 100 μm dan 500 μm untuk mengkaji kesan ke atas pencirian transistor berbanding saiz aliran. Mobiliti

elektron di dalam laluan bendalir terkesan dengan kehadiran cecair polar. Halaju elektron kini mengalami lebih banyak pelanggaran dengan molekul air yang bergerak dan polar, disertai dengan kesan medan elektrik yang dikenakan pada get. Profil laluan bendalir diperiksa dengan bantuan stilus profilometer dan SEM. Isu penutupan get di atas laluan bendalir diatasi dengan menggunakan satu lapisan kaca nipis yang telah disalut dengan aluminum pada sebelah permukaannya dan dilekatkan ke atas permukaan silikon. Tetapi teknik tersebut akan meyebabkan lebih tinggi ambang voltan kerana tebal silika ialah 80 μm dan jauh lebih tebal berbanding oksida MOSFET yang biasa. Kebiasaannya tebal lapisan oksida MOSFET adalah di sekitar 0.02 – 0.1 μm. Justeru, ia akan menyebabkan pengurangan medan elektrik di sekitar kawasan get. Ujian ke atas peranti berlansung semasa proses fabrikasi, di mana pelbagai kerintangan, ketebalan lapisan yang dihasilkan dan parameter-parameter lain diukur. Namun, ukuran-ukuran tersebut tidak dapat memberi pengertian atau pemahaman kepada prestasi akhir peranti tersebut. Oleh yang demikian, ujian elektrikal dilaksanakan bagi kedua-dua kondisi iaitu dengan dan tanpa cecair di dalam laluan bendalir dengan menggunakan alat penganalisa parametrik semikonduktor, penyurih lengkung dan litar berarus tinggi. Pencirian I-V dan kerintangan peranti dianalisa dan keputusan menunjukkan terdapat hubungan di antara arus dan voltan serta cirinya mematuhi teori. Namun demikian, peranti ini tidak dapat dikategorikan sebagai PMOS atau NMOS kerana laluan bendalir tidak didopkan. Keputusan menunjukkan rintangan berkurangan sebanyak satu tingkat bagi kondisi basah berbanding kondisi kering. Ini sekali lagi menunjukkan kehadiran molekul air di dalam laluan bendalir membantu memperbaiki mobiliti pengangkut.

FABRICATION AND CHARACTERIZATION OF MICROFLUIDIC FIELD EFFECT TRANSISTOR ON SILICON SUBSTRATE

ABSTRACT

The development of a silicon-based microfluidic field effect transistor has been carried out. The main objective of this study is to present from concept, the design of a microfluidic FET and to develop its appropriate process flow in fabricating the microfluidic FET on silicon wafer, which will finally be characterized using a suitable test methodology. Hence, fabrication on a p- <100> 4 inch silicon wafer by photolithography, wet chemical etching, thermal oxidation, diffusion and metallization with focus on a liquid conduction path has been executed. A three level photo mask has been designed via AutoCAD and chrome printed on soda-lime glass. The basic structure of the device is adapted from the conventional MOSFET structure and redesigned to incorporate a liquid channel in its operation. Therefore, the functionality remains unchanged but the principal conduction path is replaced by a fluid instead of a doped semiconductor. Two reservoirs are connected via a channel with source and drain regions doped on opposite sides of the liquid channel to reduce conduction through the substrate. They are placed as far away from each other in order to minimize electron flow through the fluidic channel when not filled with fluid. The channel widths are set to five sizes, which are 5 μm, 20 μm, 50 μm, 100 μm and 500 μm in order to study the effect of the transistor characteristics against channel size. The electron mobility in the channel is significantly affected due to the presence of polar liquid. The electron drift velocity now undergoes more collisions with mobile water molecules, which is itself polar and hence affected by the applied gate electric field. The channel profiles are inspected with the aid of stylus profilometer and SEM. The capping issue of the gate on the channel i.e. a void is addressed using a thin layer of single-side aluminum coated glass glued onto the silicon surface. This however results in higher threshold voltage as the silica thickness is about 80 μm, which is much thicker than the normal MOSFET oxide. Typically the thickness of the oxide layer in MOSFET is in the range of 0.02 - 0.1μm. Therefore, this causes higher reduction in electric field at the gate area. Testing of the devices commences during the fabrication process where the various resistivity, grown layer thicknesses and other parameters are measured. However, these measurements do not give an insight towards the final device performance. Thus, an electrical test is performed on both conditions, with and without liquid inside the channel using the semiconductor parametric analyzer, curve tracer and a high current circuit. I-V characteristics and resistivity of the devices is analysed and the results show that there is some current and voltage relation and the characteristics does conform to the theory. However, the device can not be categorized either as PMOS or NMOS since the channel is undoped. The resistance is reduced by one order for wet condition as compared to dry condition. This again shows that the presence of water molecules in the channel improves the carrier mobility.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The semiconductor industry has grown rapidly in the past few decades, driven by the microelectronics revolution. New technologies emerge with new materials and manufacturing processes that are used to create new products. Microelectronic processing has also fuelled integrated microfluidic systems which have gained interest in recent years for many applications including chemical, medical, automotive and industrial (Gad-el-Hak, 2006, p. 3-1). This chapter provides the background knowledge on which the studies are based.

1.2 Microfluidics and microfluidic devices

Microfluidics is a multidisciplinary field comprising of physics, chemistry, engineering and biotechnology which deals with the behavior, precise control and manipulation of microliter and nanoliter volumes of fluids. It has been an area of intense research, where the key aspect of microfluidics is its smallness. This attribute brings new elements which are not only quantitative, but also qualitative (Ottino & Wiggins, 2004; Karnik, Castelino & Majumdar, 2006).

The volumes involved in microfluidics can be understood by visualizing the size of a one-litre container, and then imagining cubical fractions of this container. A cube measuring 100 mm on an edge has a volume of one litre. A tiny cube whose height, width and depth are 1/1000 (0.001) of this size or 0.1 mm is the size of a small grain of table sugar. That cube will occupy 1.0 nl. A volume of 1.0 pl is represented by a cube whose height, width and depth are 1/10 (0.1) of the 1.0 nl cube. It would thus take a powerful microscope to resolve this size.

Microfluidic devices on the other hand, are devices where micron sized fluid channels fabricated on a suitable substrate to achieve a specific end application. Channels of the micro-devices are mostly silicon, glass, or quartz based and is fabricated by photolithography, etching, deposition, microwetting, and microimpression which permit the fabrication of miniaturized systems. Interconnection of channels allows the realization of networks along which liquids can be transported from one location to another on a device surface. In this way, small volumes of solution may be introduced from one channel into another, and controlled interaction of reactants is made possible (Verpoorte & Rooij, 2003). Other than channels, nozzles, pumps, mixers, valves, filter, sensors are also categorized as microfluidic devices (Permal, 2007). Typically these devices are either static or increasingly dynamic where the liquid flows through the channels and bends. The small size of the channels combined with capillary effects, pump effects (if any pump is used) and bend effects enable separation and subsequent identification of minute quantities of elements. The ability to manipulate fluids at the micron level brings in several advantages (Marr & Murakata, 2007):

1. A significant reduction of sample consumption.
2. A larger number of devices consisting of hundreds to thousands of channels and valves can be incorporated on a small planar surface allowing simultaneous parallel and complex analyses.
3. Smaller processing time for analyses and synthesis that can be done at the point of need than at a centralized laboratory (bringing laboratory to the sample).
4. The fabrication methods are based on traditional silicon-based technologies

which make them easier and cheaper to produce.

Fabrication of microfluidic devices presents new challenges for micro- and nano-engineering. With increasing demand for products associated with the medical, pharmaceutical, and analytical science industries over the past few years, much attention has been paid to the design and manufacture of microfluidic devices. Intensive research has been made especially on silicon-based microfluidic devices (Jackson, 2006). Silicon has become the material of choice for most microfluidic applications because of the well-explored microfabrication techniques of silicon itself. It makes the combination of the mechanical and electrical function in single devices possible (Verpoorte & Rooij, 2003) providing the impetus in the area of MEMS for the enormous activity over the past three decades.

Since the establishment of the field of μTAS in 1990 by Manz, Graber and Widmer, device design and process integration remains as an interesting challenge to be solved (Manz, Graber &Widmer, 1990). In this study, the focus is directed towards the fabrication technology and its related characterization which allows the realization of a silicon-based microfluidic field effect transistor.

1.3 Survey of past experimental work

From as early as 1960s, fluidic systems have been experimented with, to perform logic operations. Erickson and Li (2003) reported that modern microfluidics (Gravesen, Branebjerg & Jensen, 1993) can be traced back to the development of a silicon chip based gas chromatograph at Stanford University and the ink-jet printer at IBM. Though both these devices were quite remarkable, the concept of the integrated microfluidic device (which often fall under the broad categories of labs-on-a-chip or miniaturized total analysis systems) as it is known today was not developed until the