	のりき　あきひろ
氏　　　　名	乗　木　暁　博
授　与　学　位	博士（工学）
学位授与年月日	平成２５年３月２７日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）バイオロボティクス専攻
学位論文題目	Study of Opto-Electronic 3D LSI Technology for Heterogeneous System on Si (ヘテロジニアスシステムオンシリコン用３次元光電子集積化技術に関する研究)
指　導　教　員	東北大学教授　田中　徹
論文審査委員	主査　東北大学教授　田中　徹　　東北大学教授　小野　崇人 東北大学教授　寒川　誠二　東北大学教授　羽根　一博

論 文 内 容 要 旨

With the progress of information society, optical communication has been used for shorter distance communication in high performance computing systems. This is due to growing demands for high bandwidth communication. Currently, to realize future high performance computing systems, optical communication on LSI (Large Scale Integrated circuit) chips has been aggressively studied in many research organizations. In particular, Si photonics technology has been strongly studied to fabricate optical devices such as optical modulators, optical waveguides, and photo detectors with CMOS (Complementary Metal Oxide Semiconductor) compatible processes. On the other hand, 3D (3 Dimensional) integration technology has also attracted much attention to realize novel high performance and high functional 3D LSIs. Using the 3D integration technology, heterogeneous components such as CPUs (Central Processing Unit) and DRAMs (Dynamic Random Access Memory) can be integrated in a 3D LSI. Such 3D LSI will become a very high performance computing element of future computing systems. Moreover, higher integration of electrical devices can be realized without scaling down of the device sizes. Since physical limitation of device miniaturization has become a serious problem in recent years, the 3D integration technology will be indispensable for developing future computing systems.

As the high performance 3D LSIs require very high interconnect bandwidth, high density optical interconnection technology in the 3D LSIs has to be developed. In particular, it is required to fabricate optical interconnections on each stacked LSI chip to achieve very high density integration of the optical interconnections using the 3D integration. Such 3D integration of optical interconnections is also necessary to fabricate several types of networks of the optical interconnections in the 3D LSI. The several types of networks with different topologies or specific applications are important for efficient parallel computing. The parallel computing using many processing elements has been more important and its parallelism continues to be enhanced.　However, while 3D LSIs with optical interconnections have been proposed in several research organizations, the optical interconnections can be fabricated on only one LSI chip among stacked LSI chips. Hence, high density 3D integration of the optical interconnections is impossible.

In this work, opto-electronic 3D LSI, which is a novel 3D LSI having optical interconnections on each stacked LSI chip, has been proposed. The opto-electronic 3D LSI has both electrical and optical vertical interconnections passing through stacked LSI chips. Using such vertical optical interconnections, stacked LSI chips are optically connected and optical interconnections are realized on each stacked LSI chips. Thus, the optical interconnections can be highly integrated by the 3D integration. In addition, several types of optical interconnection networks with different topologies or specific applications can be realized in the opto-electronic 3D LSI. And also, the optical interconnections integrated on each stacked LSI chip can realize high bandwidth I/O data transfer for each LSI chip. High density TSVs (Through Si Via) which are electrical interconnections connecting stacked LSI chips and high bandwidth optical interconnections in the opto-electronic 3D LSI will realize high performance data transfer for future massive parallel high performance computing. In this work, to realize such opto-electronic 3D LSI, fabrication technologies for the vertical optical interconnections were successfully developed. And also, an optical modulator and a photo detector were studied to integrate them in the opto-electronic 3D LSI.

To realize vertical optical interconnections in the opto-electronic 3D LSI, two novel optical components, that are TSPV (Through Si Photonic Via) and UDOC (Uni-Directional Optical Coupler), were proposed and fabricated. The TSPV is optical waveguides passing through LSI chips. As such through Si optical interconnections, there are competing technologies such as free space optical interconnections and polymer optical waveguides in a Si substrate. In contrast, it was shown that TSPVs can achieve very high density optical interconnections compared with the other possible optical interconnections since the TSPV has relatively high refractive index difference between core and cladding. Core material of the TSPV is Si and cladding material is SiO_2 or polymer. As a fabrication technology of the TSPV, a technology to fill epoxy resin in trenches of the TSPV was proposed and developed. By using such epoxy resin filling technology, cladding was fabricated successfully without any voids or cracks. There were also no negative effects on Si core by the epoxy resin filling. And also, technology for simultaneous fabrication of TSPVs and TSVs was successfully demonstrated. Using O_3-TEOS (Tetraethyl orthosilicate) CVD (Chemical Vapor Deposition) and SOG (Spin on Glass) spin-coating, TSPVs and TSVs were simultaneously fabricated, and thus, cost reduction can be realized. As an evaluation of fabricated TSPVs, two types of optical interconnections were evaluated with and without the TSPVs passing through a Si substrate with the thickness of 50 μm. The width and the pitch of the optical interconnections were 7.5 μm and 13 μm, respectively. As a result of evaluation, it was confirmed that light was successfully confined in the TSPV core and transferred through the Si substrate while there were cross talks between neighboring optical interconnections without the TSPV.

In order to connect the TSPVs and planar Si optical waveguides on the LSI chip, the UDOC was proposed. Compared with the other conventional optical coupler, the UDOC can realize relatively high coupling efficiency between the TSPV and the planar optical waveguide. To realize high efficient UDOCs, several structural parameters have to be optimized. Optimum grating pitch, top mirror distance, and side mirror distance were designed theoretically. Following the theoretical design of structural parameters of the UDOC, these parameters were optimized by using FDTD (Finite-Difference Time-Domain) simulation. Grating depth which is another structural parameter of the UDOC was also optimized by using FDTD simulation. As a result of optimization, the UDOC can achieve coupling efficiencies around 85 %. It was also confirmed by FDTD simulation that the high efficient optical coupling can be realized by using the same designed UDOC for both directions between the TSPV and the planar optical waveguide. Then, fabrication tolerance of the UDOC was evaluated by FDTD simulation and it was shown that there were not critical structural parameters to realize the high efficient UDOC. Finally, fabrication technology of the UDOC was developed by using standard CMOS technology. To form SiO_2 layer with flat surface on the fabricated grating structure, spin-coating of SOG and PECVD (Plasma Enhanced Chemical Vapor Deposition) were compared. After SiO_2 layer formation on the grating structure, spin-coating of SOG can realize the flat surface of the SiO_2 layer while PECVD cannot realize that. Therefore, using spin-coating of SOG, the flat SiO_2 surface can be obtained on the grating structure without any planarization process like CMP (Chemical Mechanical Polishing). To evaluate optical behaviors of fabricated UDOCs, the Si under the BOX of the SOI wafer, where the UDOCs were fabricated, was removed. The UDOCs were irradiated with 1.55-μm laser light from BOX surface by using an optical fiber. The power of the irradiated laser light was 1 dBm. Light coupled to the planar Si optical waveguide by the UDOC was output from the Si optical waveguide and detected by a near-infrared light power meter. As a result of the fabricated UDOC evaluation, side mirror distance dependences of measured coupling efficiency were almost consistent with those of simulated efficiency. Therefore, the UDOCs were successfully fabricated and functioned as the high efficient optical couplers. The grating pitch dependence of measured coupling efficiency was almost consistent with that of simulated efficiency, however, there were large difference in some grating pitches between measured and simulated efficiency. This would be caused by fabrication variations of the side mirror distance. At the power meter, measured absolute peak optical power was -13.3 dBm, thus the optical loss was -14.3 dB. This optical loss includes fiber-to-UDOC coupling loss, Si optical waveguide loss (waveguide length was 10 mm), waveguide-to-power meter coupling loss, and UDOC coupling loss. Therefore, the predicted coupling loss of the UDOC will be smaller than -14.3 dB.

Compact, low energy consumption, and high reliability optical modulators are strongly required for optical interconnections on the LSI chip. Currently, there are two major optical modulators. One of the modulator is a MZI (Mach-Zehnder Interferometer) based optical modulator (MZI modulator). The MZI modulator has high reliability, however, its size and energy consumption are relatively large due to small electro-optical effects in Si. Another modulator is a ring resonator based optical modulator (ring modulator). Among conventional optical modulators, the ring modulator is the most promising candidates as a compact and low energy consumption optical modulator. However, its reliability is extremely low due to its low tolerances for fabrication variations and temperature fluctuations. To realize a compact, low energy consumption, and high reliability optical modulator, the NRR modulator

(Non-Reciprocal Resonator based optical modulator) was proposed in this dissertation. Since the NRR modulator was based on the ring modulator, it is very compact and low energy consumption. In addition, to overcome the low reliability of the ring modulator, non-reciprocity of MO (magneto-optical) effects was used in the NRR modulator. The low reliability of the ring modulator is caused by its optical modulation mechanism using two ring resonators. The optical modulation using the ring modulator is realized by electrical control of relationships between two resonant wavelengths of the two ring resonators. The one ring resonator is used as the component of the ring modulator and another one is used as a passive wavelength filter. The resonant wavelength of the one ring resonator used for the ring modulator can be electrically tuned. Thus, electrical control of the relationship between two resonant wavelengths of the two ring resonators can be realized. By using such control of the relationship, intensity of light passing through the two ring resonators can be modulated. However, the fabrication variations and temperature fluctuations between the two ring resonators also change the relationship. The effects of the fabrication variations and the temperature fluctuations on the relationship are as large as that induced by electrical control. Therefore, reliability of the ring modulator is extremely low due to its low tolerances for the fabrication variations and temperature fluctuations. On the other hand, in the NRR modulator, the two optical resonances of the two ring resonators used in the conventional ring modulator were replaced by a clockwise resonance and a counter-clockwise resonance of the one ring resonator. Therefore, unlike the conventional ring resonator, the fabrication variations and the temperature fluctuations between two ring resonators do not occur. Thus, the NRR modulator also has high reliability. Control of the relationship between two resonant wavelengths of the clockwise and the counter-clockwise resonances can be realized by using non-reciprocity of MO effects. A ring resonator with the non-reciprocity has different resonant wavelengths for clockwise resonance and counter-clockwise resonance, while a reciprocal ring resonator which is a standard ring resonator has the same resonant wavelength. Therefore, by switching reciprocal and non-reciprocal state of a ring resonator, the relationship between two resonant wavelengths of clockwise and counter-clockwise resonances can be controlled. As a result, the NRR modulator is small size, low energy consumption, and high reliability optical modulator. By the 3D FDTD simulation, the predicted optical modulation of the NRR modulator was confirmed. In 3D FDTD simulation, the extinction ratio of the NRR modulator was around 10 dB at the maximum. A Cu wiring is integrated in the NRR modulator to apply magnetic field to switch the reciprocal and non-reciprocal state of the ring resonator. Power dissipation of the NRR modulator depends on current flow in the Cu wiring. The amount of the current in the Cu wiring was estimated to evaluate the power dissipation of the NRR modulator. While the required maximum magnetic field was 50 Oe, the magnetic field can be reduced around 10 Oe. To apply the magnetic field of 50 and 10 Oe, the relatively small power dissipation of 267.4 and 10.7 μW were required respectively. When the NRR modulator operates at 1 Gbps, those energy consumptions corresponded to only 267.4 fJ/bit and 10.7 fJ/bit, respectively. These energy dissipations are relatively small compared with the other optical modulators. On the other hand, in the case of magnetic field of 50 Oe, relatively large amount of current and current density were required. Therefore, it is necessary to operate the NRR modulator by the magnetic field around 10 Oe or less. To apply the 10-Oe-magnetic field, the required amount of current and current density were around 5 mA and 1 MA/cm^2, respectively.

To integrate Ge MSM (Metal-Semiconductor-Metal) photo detectors in the opto-electronic 3D LSI, a new Ge photo detector integration technology was proposed and developed. To integrate high quality Ge MSM photo detectors, it is the most preferable to transfer fabricated Ge photo detectors from a Ge substrate to a SOI substrate where electrical and optical devices are already integrated. Therefore, a SOG bonding method which uses SOG as an adhesive between the Ge substrate and SOI substrate was developed. By controlling the heating profiles for the SOG bonding method, the Ge and Si substrate can be successfully bonded with small gap of around 100 nm. Therefore, using the SOG bonding method, relatively high efficient evanescent coupling can be realized. The Ge MSM photo detector was fabricated for the integration on a Si optical waveguide. Basic characteristics of the fabricated detector were evaluated and it was confirmed that the fabricated detector could successfully detect near infrared light.

As a result of this work, key technologies of the opto-electronic 3D LSI were developed. The opto-electronic 3D LSI will realize the future high performance computing systems.

論文審査結果の要旨

人と人，人とモノ，モノとモノが遍くつながることで，膨大な量のデータが発生し，処理され，新しい価値が創造されている。このような世界を実現しているのは，極めて小型高性能化した情報処理装置と通信装置であることは言を俟たない。これらの装置の小型高性能化は微細化による半導体集積回路(LSI)の大規模化，高密度化，高性能化に支えられている。また，膨大な量のデータ伝送は配線の大容量化と高周波化によって実現されている。しかし近年では静的消費電力の増大や動作速度の飽和により微細化しても LSI 性能が向上しないという問題が生じている。一方，LSI 配線の狭ピッチ化と電気信号の高周波化に伴い信号遅延や信号劣化といった問題も深刻化し，電気配線による信号伝送がボトルネックとなって高性能な情報処理装置や通信装置の実現が困難となっている。このような状況の中，微細化に依らない高性能化技術や，従来の電気信号伝送よりも高速，大容量，低消費電力の光信号伝送技術に関する研究開発が世界中で精力的に行われている。特に，長さ数十 μmの極めて短いシリコン貫通配線(Through Si Via;TSV)を用いてLSI を積層した 3 次元集積回路と，LSI 内部での大容量データ伝送を可能にする光配線が注目されている。本論文は，微細化とは異なるLSI 高性能化技術である 3 次元集積化とLSI 内光伝送を同時に実現する 3 次元光電子集積化技術について研究成果をまとめたもので，全編 6 章からなる。

第 1 章は序論であり，本研究の背景，目的および構成を述べている。

第 2 章では，従来の光電子集積回路の概要を述べるとともに課題を明らかにしている。その後，課題に対する解決策に言及し，全ての課題を解決すると同時に異種デバイス集積による機能融合を実現できるヘテロジニアスシステムオンシリコン用 3 次元光電子集積化技術を提案している。この技術により，光配線層を積層した全 LSI 内に形成して相互に高効率で接続できる。また，提案技術には新原理による光変調器も含まれている。LSI の情報処理性能とデータ伝送性能を飛躍的に高める集積化技術の提案であり，重要な成果である。

第 3 章では，積層した全 LSI 内に縦方向に光を伝送するシリコン貫通光配線(Through Silicon Photonic Via;TSPV)と，TSPV を伝送してきた光を LSI 内に横方向に導入する一方向光結合器(Uni-Directional Optical Coupler; UDOC)の提案，作製技術の確立，性能検証を行っている。TSPV のコア材料には屈折率の大きな Si を用いているため，微細高密度の縦方向光配線を実現できる。また，TSV と TSPV を同時作製する技術開発にも成功している。UDOC はサイドミラーとトップミラーからなるミラー構造とグレーティング構造を併せ持つために極めて高い光結合効率を有し，UDOC 構造を最適化することにより約 83%のカップリング効率を実現できる。3 次元光電子集積化技術の最も重要な基盤技術を確立したものであり，有益な成果である。

第 4 章では，磁気光学材料によりマイクロリング共振器の相反性状態を変化させることで信号光を変調する非相反性共振器(Non-Reciprocal Resonator; NRR)を用いた光変調器を提案し，FDTD シミュレーションによる原理検証と性能評価を行っている。1 つのリング共振器で光変調が可能なため，従来よりも格段に小型かつ高信頼性を実現できる新原理に基づく光変調器の発明であり，特筆すべき成果である。

第 5 章では，ゲルマニウム(Ge)光検出器を接着によりシリコン光配線上にインテグレーションする 3 次元光電子集積化技術の提案，及び Ge 光検出器の作製と電気特性検証を行っている。既に作製してある光電子集積回路にダメージを与えずに Ge 光検出器をインテグレーションする技術であり，実用化に向けた有用な成果である。

第 6 章は結論である。

以上，要するに本論文は，3 次元集積によるLSI 高性能化と異種デバイスとの機能融合，及び積層した全 LSI 内光伝送による超高速信号伝送を可能にするヘテロジニアスシステムオンシリコン用 3 次元光電子集積化の基盤技術開発に成功し，実用上重要な結果を得ているものであり，バイオロボティクスおよび半導体工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。