ISHIWARA Hiroshi "Creation of Highly Functional Silicon ICs Using New Materials"

1. Biography

Born on 6th November, 1945

1968 Bachelor of Engineer. (Electronics), Tokyo Inst. Tech.

1973 Doctor of Engineer. (Electronics), Tokyo Inst. Tech.

1973 Research Associate, Faculty of Engineer. Tokyo Inst. Tech.

1976 Associate Professor, Interdisciplinary Graduate School of Sci. & Engineer. Tokyo Inst. Tech.

1989 Professor, Precision and Intelligence Lab. Tokyo Inst. Tech.

1998 Professor, Frontier Collaborative Research Center, Tokyo Inst. Tech.

2004 Dean of Interdisciplinary Graduate School of Sci. & Engineer. Tokyo Inst. Tech.

2006 Professor, Interdisciplinary Graduate School of Sci. & Engineer. Tokyo Inst. Tech.

2008 President, The Japan Society of Applied Physics (-2009)

2008 Member, Science Council of Japan (-2014)

2010 WCU (World Class Univ.) Professor, Konkuk Univ. Korea (-2013)

2011 Professor Emeritus, Tokyo Inst. Tech.

The Order of the Sacred Treasure, Gold Rays with Neck Ribbon; Japanese Government (2019), Fellow; Mater. Res. Soc. (2011), Fellow; The Institute of Electrical Engineers of Japan (2011), Honorary Member; The Japan Society of Applied Physics (JSAP) (2011), Nippon Keidanren Chairman's Award for Industry-Academia Collaboration (2011), SSDM Award (2008), Nano Korea Minister of Sci. and Technol. (Deputy Prime Minister) Award (2007), Medal with Purple Ribbon; Japanese Government (2003), JSAP Outstanding Paper Award (2003), Fellow; The Institute of Electronics, Information and Communication Engineers (2002), Fellow; IEEE (2001), The Ichimura Prizes in Technology - Meritorious Achievement Prize (1994), The Inoue Prize for Science (1994), The Japan IBM Science Prize (1990)

2. Research Summary

Ishiwara's research was conducted with the aim of introducing new conductive, insulating, and dielectric materials into silicon (Si) integrated circuits to enhance circuit functionality. In 2.1, he explored film materials that grow well as single crystals on Si substrates, and found that cobalt silicide ($CoSi_2$) and fluorite (CaF_2) were excellent as conductive and insulating films, respectively. Single-crystallization of conductive and insulating films using these new materials is expected to improve the performance of integrated circuits and enable the realization of three-dimensional integrated circuits with stacked transistors. Next, in 2.2, he pointed out that memory-type transistors using ferroelectrics such as bismuth strontium tantalate ($SrBi_2Ta_2O_9$) as gate dielectrics are useful for weight storage of synaptic connections in neural networks, and experimentally showed that a neurochip integrated with this transistor exhibits an adaptive learning function in which the operating characteristics gradually change while the circuit is in use. In 2.3, he showed that optimizing the material and structure of the ferroelectric-gate transistors can significantly improve the data retention period. Ferroelectric memory is now widely used as memory for contactless IC cards and smart electricity meters because of its low power consumption and non-volatility.

2.1 Research on Silicon Heterostructure Devices

In the late 1970s, when Ishiwara began his research on improving the performance and functionality of semiconductor integrated circuits, the insulating and conductive films used in semiconductor devices were composed of amorphous or polycrystalline materials. In this context, Ishiwara recognized the importance of insulating, dielectric, and conductive materials and showed that the performance of semiconductor integrated circuits could be greatly improved by making these materials more functional. It is notable that he foresaw the importance of such non-semiconductor materials in semiconductor devices more than 40 years ago, when the microfabrication technology was at its peak.

First, Ishiwara showed that new device structures can be realized by changing insulating and conducting films from amorphous or polycrystalline phase to single crystalline one. That is, he predicted based on a literature survey that fluorite (CaF_2) and cobalt disilicide ($CoSi_2$) are excellent candidate materials for insulating and conductive films, respectively, and succeeded in growing their single crystalline films on silicon (Si) substrates by optimizing the deposition conditions. Furthermore, he succeeded in growing single crystalline Si films on them, and realized for the first time in the world a structure in which single crystalline insulating and conducting films are embedded in single crystalline Si [1,2].

When Ishiwara started his research, there were few researchers who paid attention to metal silicides such as $CoSi_2$, but they later attracted attention as a conductive material with high heat resistance, and are now widely used as electrodes in integrated circuits. In addition, the structure in which an insulating film is embedded in Si is called SOI (silicon on insulator) structure, and it has become an important structure for achieving higher operation speed and lower power consumption of integrated circuits. This research, together with the subsequent discovery of high-temperature superconducting materials, has led to the common fabrication of single crystalline stacked structures consisting of materials with significantly different electrical and magnetic properties (heterostructures). However, to date, no material has been found that grows better as a single crystal on Si substrates than the materials discovered by Ishiwara, both for insulating and conducting films.

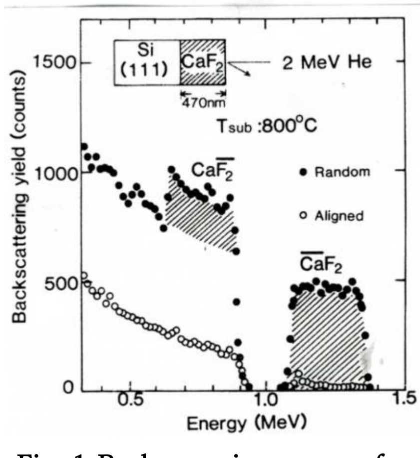

Fig. 1 Backscattering spectra for CaF_2/Si structure. The decreased aligned yield shows that the film grows as a single crystal.[2]

2.2 Research on Learning Neurochips Using Ferroelectric Memory

With regard to dielectric films, Ishiwara focused on ferroelectric films and conducted research on ferroelectric memory, which can read and write information with the operating speed of computers and whose memory contents do not disappear even when the power is turned off (non-volatility). There are two types of ferroelectric memory: a capacitor type that stores information in a ferroelectric capacitor, and a transistor type that stores information in a ferroelectric-gate transistor (a transistor whose gate material is composed of ferroelectric material). The transistor type has been studied for a long time because of its features of miniaturization based on the scaling rule and high-speed readout, but research has been half-abandoned because of the difficulty in fabricating ferroelectric-gate transistors. For this reason, it is the capacitor type that has been put to practical use as memory for IC cards and smart electricity meters.

Ishiwara proposed to use this ferroelectric-gate transistor as analog memory for weight storage of synaptic connections in artificial neural networks. He also showed that, when combined with pulse frequency modulation operations, an adaptive learning function can be realized in which the operating characteristics gradually change while the network is in use, and that if the transistors are regularly arranged on an SOI substrate, a high-density synaptic connection circuit can be formed to perform weighted sum-of-product operations [3]. Experimentally, he fabricated an integrated circuit incorporating ferroelectric-gate transistors and realized the world's first neurochip that learns based on the properties of the material without the need for digital arithmetic processing [4].

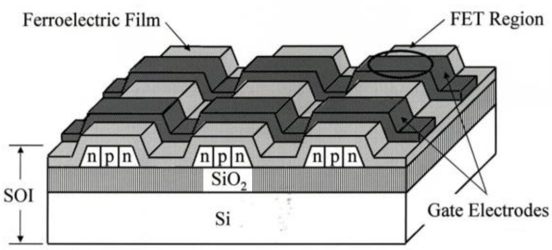

Fig.2 Proposed sum-of-product operation circuits on an SOI substrate.[3]

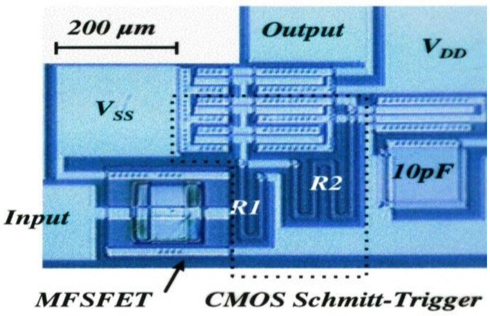

Fig.3 A learning type neurochip formed on an SOI substrate.[4]

2.3 Research on Improving the Performance of Ferroelectric Memory

Ishiwara has made significant achievements in research to improve the capacity, speed, and power consumption of ferroelectric memory. In order to achieve these goals simultaneously, it is important to optimize the memory cell structure as well as the search for new ferroelectric materials, and thus he organized a joint research project among industry, government and academia (NEDO: Research and development of next-generation ferroelectric memory, 1999-2004). In this project, he proposed a high-density cell structure in which each memory cell consists of only one ferroelectric-gate transistor, and devised a new circuit model of a ferroelectric capacitor in which the amount of stored charge changes according to the applied voltage history, and realized a high-precision simulation of the memory circuit operation.

In addition, experimentally, he clarified that inserting a thin film of hafnia (HfO_2) between the gate ferroelectric film and the Si substrate prevents the diffusion of the constituent elements and extends the data retention period more than 10 times longer than previously reported [5]. With these research results as a starting point and further improvements in gate materials, ferroelectric-gate transistors are now being actively researched not only for memory applications, but also as transistors for logic applications where current is switched on and off at high speed and low voltage.

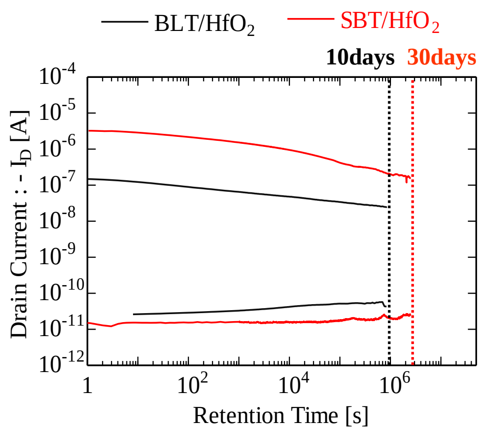

Fig.4 Data retention characteristics of ferroelectric-gate transistors.[5)]

Ishiwara has also been searching for new ferroelectric materials, and has found that when Si elements are added to typical ferroelectric materials such as $Pb(Ti,Zr)O_3$ and $SrBi_2Ta_2O_9$, the ferroelectric properties are significantly improved when thin films are made, and operation at low voltages becomes possible [6], and that the addition of manganese (Mn) element is effective in reducing the leakage current of bismuth ferrite ($BiFeO_3$), which has a large amount of stored charge but could not be used at room temperature due to its large leakage current [7]. Furthermore, he revealed that even Teflon-based organic ferroelectric films such as P(VDF-TrFE) can be operated at voltages as low as 3 V by using ultra-thin films, opening up the possibility of organic ferroelectric memory using plastic substrates [8].

3. Ripple Effects of Research Results and Activities other than Research

3.1 Ripple Effects of Research Results

Ishiwara's research on Si heterostructure devices, in which heterostructures are formed by growing single crystalline insulating and conducting films on Si substrates, was so novel that a new symposium field was established in Mater. Res. Soc. He served as an organizer of this symposium (1988) and gave 18 invited talks on Si heterostructure devices at this and other symposia. Nowadays, the technique of stacking various films with different electrical and magnetic properties as a single crystal is widely used as an indispensable technology to improve the performance of quantum effect, superconducting, and spintronics devices.

He has also made achievements in ferroelectric memory as described in the previous section, and has given a total of 40 invited talks at international conferences and symposia on ferroelectric memory, as well as at the IEEE International Electron Devices Meeting (IEDM) and Device Research Conference (DRC). In addition, the circuit model of ferroelectric capacitors developed through the NEDO project is used for high-precision simulation of memory circuit operation in the development and production in companies. In terms of publications, Ishiwara has authored more than 400 original papers, including the following representative papers, with a total of more than 9,000 citations and an h-index of 50 (50 papers cited more than 50 times). From these results, it can be said that the academic ripple effect of his research results and his contribution to academic society activities are extremely significant.

3.2 Activities other than Research

In addition to his teaching and research activities at the Tokyo Institute of Technology, Ishiwara was invited to the Department of Physics at Konkuk University as a visiting professor from March 2010 to August 2013 under the World Class University program established by the Korean government, and contributed to academic exchange between Japan and Korea.

He has also served as Executive Director of the Japan Society of Applied Physics (1991-1992), Vice President (2006-2007), President (2008-2009), Chairman of the Organizing Committee of the 36th Intern. Conf. on Solid State Devices and Materials (2004), President of the Electronics Society in the IEICE (2000), Member of the Editorial Board of Applied Physics Review (1992-2011), Member of the Science Council of Japan (2008.10-2014.9). In addition, he has served as a director, councilor, or selection committee member of Asahi Glass Foundation, Casio Science Promotion Foundation, Marubun Research Promotion Foundation, Inamori Foundation, Canon Foundation, Ichimura Foundation for New Technology, and The Foundation of Ando Laboratory.

【Representative Papers】 (Number of citation based on "Research gate" (13 Dec. 2021))

1. S.Saitoh, H.Ishiwara and S.Furukawa; "Double heteroepitaxy in the Si(111)/$CoSi_2$/Si structure", Appl. Phys. Lett., 37 (1980) 203 【No. of citation, 174】
2. H.Ishiwara and T.Asano; "Silicon/insulator heteroepitaxial structures formed by vacuum deposition of CaF_2 and Si", Appl. Phys. Lett., 40 (1982) 66 【No. of citation, 173】
3. H.Ishiwara, "Proposal of adaptive-learning neuron circuits with ferroelectric analog-memory weights", Jpn. J. Appl. Phys., 32 (1993) 442 【No. of citation, 156】
4. S-M.Yoon, E.Tokumitsu and H.Ishiwara; "Ferroelectric neuron integrated circuits using $SrBi_2Ta_2O_9$-gate FET's and CMOS Schmitt-trigger oscillators" IEEE Trans. on Electron Devices, 47 (2000) 1630 【No. of citation, 25】
5. K.Aizawa, B-E.Park, Y.Kawashima, K.Takahashi and H.Ishiwara; "Impact of HfO_2 buffer layers on data retention characteristics of ferroelectric-gate field effect transistors", Appl. Phys. Lett., 85 (2004) 3199 【No. of citation, 103】
6. T.Kijima and H.Ishiwara; "Si-substituted ultrathin ferroelectric films", Jpn. J. Appl. Phys., 41 (2002) L716 【JSAP Outstanding Paper Award: No. of citation, 62】
7. S.K.Singh, H.Ishiwara, and K.Maruyama; "Room temperature ferroelectric properties of Mn-substituted $BiFeO_3$ thin films deposited on Pt electrodes using chemical solution deposition", Appl. Phys. Lett., 88 (2006) 262908 【No. of citation, 343】
8. S.Fujisaki, H.Ishiwara, and Y.Fujisaki; "Low-voltage operation of ferroelectric poly(vinylidene fluoridetrifluoroethylene) copolymer capacitors and metal-ferroelectric-insulator-semiconductor diodes", Appl. Phys. Lett., 90 (2007) 162902 【No. of citation, 176】

(Presented by ISHIWARA, Hiroshi on 13 Dec 2021)