AIP Applied Physics Letters

Chemical beam epitaxial growth of Sidoped GaAs and InP by using silicon tetraiodide

Shigekazu Izumi, Norio Hayafuji, Kazuhiko Ito, Kazuhiko Sato, and Mutsuyuki Otsubo

Citation: Applied Physics Letters **68**, 3102 (1996); doi: 10.1063/1.116436
View online: http://dx.doi.org/10.1063/1.116436
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/68/22?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Sidoped and undoped Ga1−x In x Sb grown by molecularbeam epitaxy on GaAs substrates
J. Appl. Phys. **80**, 6556 (1996); 10.1063/1.363678

Fabrication of laterally selected Si doped layer in GaAs using a lowenergy focused ion beam/molecular beam epitaxy combined system
J. Vac. Sci. Technol. B **14**, 3938 (1996); 10.1116/1.588699

Characterization of GaAs layers grown by molecular beam epitaxy
AIP Conf. Proc. **378**, 245 (1996); 10.1063/1.51218

Realtime investigation of In surface segregation in chemical beam epitaxy of In0.5Ga0.5P on GaAs (001)
Appl. Phys. Lett. **68**, 3579 (1996); 10.1063/1.116643

Growth and electrical characterization of Si deltadoped GaInP by low pressure metalorganic chemical vapor deposition
J. Appl. Phys. **79**, 8054 (1996); 10.1063/1.362359

Confidently measure down to 0.01 fA and up to 10 PΩ
Keysight B2980A Series Picoammeters/Electrometers
View video demo>
KEYSIGHT TECHNOLOGIES

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 137.189.170.231 On: Fri, 19 Dec 2014 00:04:15

Chemical beam epitaxial growth of Si-doped GaAs and InP by using silicon tetraiodide

Shigekazu Izumi,[a)] Norio Hayafuji, Kazuhiko Ito, Kazuhiko Sato, and Mutsuyuki Otsubo
Optoelectronic & Microwave Devices Laboratory, Mitsubishi Electric Corporation, 4-1 Mizuhara, Itami, Hyogo 664, Japan

(Received 30 January 1996; accepted for publication 20 March 1996)

Silicon tetraiodide (SiI_4), which has a very weak Si–I bond strength (70 kcal/mol), is successfully employed as a novel Si dopant in the chemical beam epitaxy of GaAs and InP. No precracking is necessary before supplying SiI_4 with He carrier gas. High electrical quality is ascertained for both GaAs and InP with linear Si doping controllability in the range from 2×10^{16} to 6×10^{18} cm^{-3} with a uniformity of less than 2% within a 3-in.-diam area. The electron mobility in a GaAs with a carrier concentration of 1×10^{17} cm^{-3} is 4400 cm^2/V s and that in InP with a carrier concentration of 4×10^{17} cm^{-3} is 2400 cm^2/V s, respectively. Abrupt interfaces and precise on-off controllability without any memory effect is also confirmed by secondary-ion-mass, spectroscopy measurements. The electrical activation ratio of Si in SiI_4 for both GaAs and InP is almost 100% in the range studied here. These versatile features suggest that SiI_4 is a promising candidate as a Si dopant source for chemical beam epitaxy growth. © *1996 American Institute of Physics.*
[S0003-6951(96)01022-4]

Silicon (Si) is one of the most commonly used *n*-type dopants for III–V compound semiconductors due to its low thermal diffusivity and low surface segregation. Elemental Si in a Knudsen cell is often used for Si doping in conventional molecular beam epitaxy (MBE) and gas source MBE (GS-MBE), while it cannot be used in chemical beam epitaxy (CBE) or metalorganic molecular beam epitaxy (MOMBE) due to the organic passivation of the Si atoms.[1] The preferred vapor source of Si used mainly for metalorganic chemical vapor deposition (MOCVD) is SiH_4 and Si_2H_6. The precracking of SiH_4 is required for efficient doping in InP and InGaAs for use in CBE because growth temperature is approximately 100 °C lower than that for GaAs.[2] Since Si_2H_6 is found to be easily decomposed compared to SiH_4, Si_2H_6 has been mainly used for the growth of InP-related materials.[3–5] The carrier concentration up to 1.4×10^{18} cm^{-3} was obtained with CBE-grown InP by Si_2H_6.[5] Controllability especially at a low-doping level, however, is still insufficient for device applications as the collector layer of heterojunction bipolar transistor (HBT). Many researchers have experimented with various dopant sources, such as triethylsilane (TESiH),[6] diethyltelluride (DETe),[6] tetraethyltin (TESn),[6,7] and tertiarybutyloctasilacubane [$(tBuSi)_8$].[8] Recently, it has been reported that Si doping efficiency and controllability are improved for InP and InGaAs growth by using silicon tetrabromide ($SiBr_4$),[9,10] which has a relatively weak (87.9 kcal/mol) Si–Br bond strength,[11] which suggests that the facile decomposition of Si is inevitable for a Si dopant source.

In this letter, we show the versatility of silicon tetraiodide (SiI_4), which has a very weak Si–I bond strength (70 kcal/mol)[11] as a novel Si dopant source for CBE growth of GaAs and InP through the electrical characterization.

Si-doped GaAs and InP were grown by CBE on undoped GaAs and Fe-doped InP(100) 3-in.-diam substrates. The GaAs layer was grown at 510 °C with a growth rate of 0.65 μm/h by using triethylgallium (TEGa) and arsine (AsH_3). The InP layer was grown at 460 °C with a growth rate of 0.5 μm/h by using trimethylindium (TMIn) and phosphine (PH_3). The Si dopant was specially provided 5*N* grade purity SiI_4, which was supplied with helium (He) carrier gas through a mass flow controller without any precracking. The boiling and melting points of SiI_4 are 288 and 120.5 °C, respectively. Here 10% Si_2H_6 diluted with hydrogen (H_2) was used as a reference in some experiments. Hall measurements have been performed at room temperature using the Van der Pauw method to determine the net electron concentration and mobility. Secondary-ion-mass spectrometry (SIMS) was performed with Cs^+ beam to evaluate the Si doping profile.

Figure 1 shows the dependence of the net carrier concentration and electron mobility in GaAs and InP on flow rate of SiI_4 diluted with He carrier gas. The net electron concentration increases from 2.0×10^{16} (at 0.2 sccm) to 2.7×10^{18} cm^{-3} (at 10 sccm) in GaAs and from 3.7×10^{17} (at 1 sccm) to 5.7×10^{18} cm^{-3} (at 10 sccm) in InP (at the SiI_4

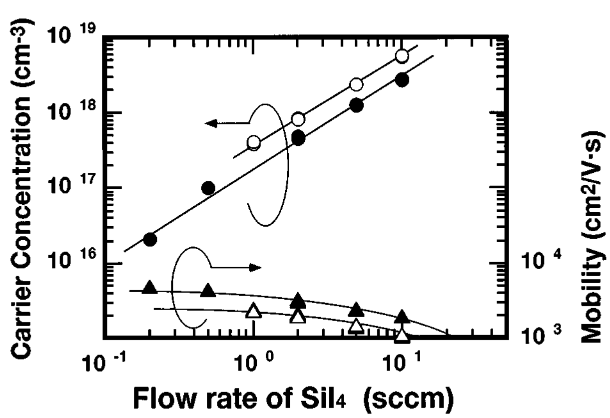

FIG. 1. Dependence of net carrier concentration and electron mobility in GaAs (○, △) and InP (●, ▲) on flow rate of SiI_4 diluted with He carrier gas. The temperature of SiI_4 bubbler was maintained at 50 °C.

[a)]Electronic mail: izumi@oml.melco.co.jp

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 137.189.170.231 On: Fri, 19 Dec 2014 00:04:15

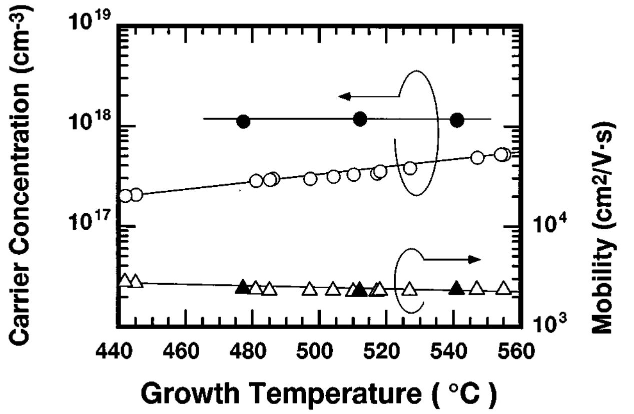

FIG. 2. Net carrier concentration and electron mobility of *n*-GaAs doped by SiI_4 (●, ▲) and Si_2H_6 (○, △) as a function of growth temperature. The AsH_3 flow rate was maintained at 4.5 sccm.

temperature of 50 °C). High electrical quality was obtained for both GaAs and InP with linear Si doping controllability. The different Si incorporation efficiency between GaAs and InP at the same SiI_4 flow rate was due to the machine's configuration. The higher the temperature SiI_4 goes, the higher the net carrier concentration becomes with the activation energy of 1.6 eV (at 2 sccm). The maximum net carrier concentrations obtained for GaAs and InP were 6.1×10^{18} at 7 sccm and 1.7×10^{19} cm^{-3} with a SiI_4 flow rate of 10 sccm at 60 °C. Since the flow rate of SiI_4 in our CBE system is controllable in the range between 0.2 and 10 sccm, precise doping control can be achieved in the range between 2×10^{16} and 2.7×10^{18} cm^{-3} in GaAs, which are adequate for the collector and emitter of AlGaAs/GaAs or InGaP/GaAs heterojunction bipolar transistor (HBT), respectively. Surface morphology is quite fine as well, even for heavily Si-doped GaAs and InP. The electron mobilities of the GaAs layers doped by SiI_4 are comparable to these using elemental Si. These InP layers are also comparable to these reported by such as Jackson *et al.*[9] The dependence of the net carrier concentration and mobility for *n*-GaAs layers grown by using SiI_4 on the growth temperature and III/V ratio is compared in Figs. 2 and 3 with those for *n*-GaAs layers grown by using Si_2H_6. The net carrier concentration of GaAs layers grown by SiI_4 is constant in the entire growth temperature and III/V ratio ranges investigated, in contrast to Si_2H_6 doping. This results in excellent uniformity. The uniformity of the sheet resistance, defined by (standard deviation/average) over 3-in.-diam *n*-GaAs and *n*-InP layers grown by SiI_4, is less than 2%, while that by Si_2H_6 is higher than 8%.

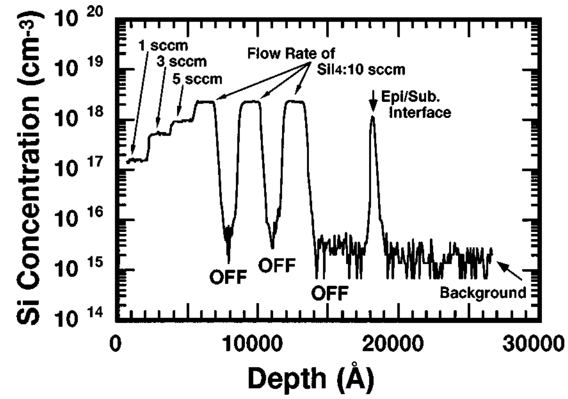

FIG. 4. SIMS profile of Si-modulation-doped GaAs layer by using SiI_4.

Figure 4 shows the SIMS profile of a Si-modulation-doped GaAs layer by using SiI_4. Abrupt interfaces and precise on-off controllability were obtained without any memory effect. In addition the Si concentration was held constant in each doped region step. Furthermore, SiI_4 does not introduce any other impurities, such as iodine, oxygen, or sulfur. The relation between carrier concentration and Si concentration in Si-doped GaAs by using SiI_4 and Si_2H_6, and Si-doped InP by using SiI_4 is shown in Fig. 5. The electrical activation ratio of Si in SiI_4 for both GaAs and InP is almost 100% in the range studied, while that in Si_2H_6 is 80% or less. These versatile features are thought to be due to the very weak Si–I bond strength in SiI_4 (70 kcal/mol). On the other hand, Si in Si_2H_6 has a Si–Si bond and three Si–H bonds whose energy is stronger than the Si–I bond, which might promote atomic Si formation and incorporation into GaAs and InP.

The growth rates for both GaAs and InP were constant over a wide doping range, indicating that there was little

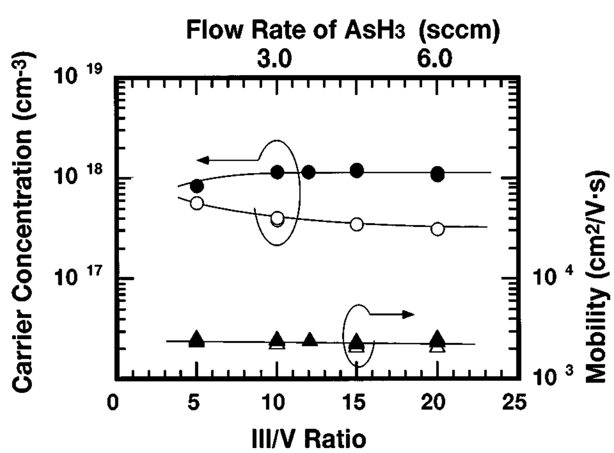

FIG. 3. Net carrier concentration and electron mobility of *n*-GaAs doped by SiI_4 (●, ▲) and Si_2H_6 (○, △) as a function of III/V ratio. The growth temperature was maintained at 510 and 520 °C for using SiI_4 and Si_2H_6, respectively.

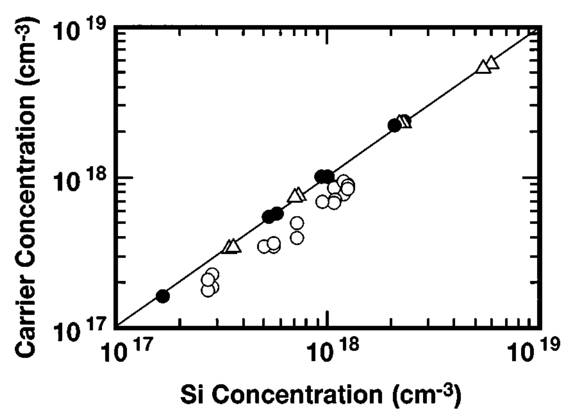

FIG. 5. Relation between carrier concentration and Si concentration in Si-doped GaAs by using SiI_4 (●), by using Si_2H_6 (○), and Si-doped InP by using SiI_4 (△).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 137.189.170.231 On: Fri, 19 Dec 2014 00:04:15

etching with iodine (I) radicals. While carbon doping by CCl_4 promotes the etching of the grown layer at a high flow rate condition,[12] Si doping by SiI_4 eliminates this kind of problem due to a very low flow rate (high doping efficiency) and growth has been performed under a reduced SiI_4 flow rate. The growth rate for both GaAs InP did not change in spite of heavy doping due to the very low etching effect of the iodine, although a dependence of the alloy composition of $In_yGa_{1-y}P$ on the flow rate of SiI_4 was observed at a higher doping level than 1×10^{18} cm^{-3}. As the flow rate of SiI_4 increases from 5 to 10 sccm, the In composition in InGaP (y) decreases from 48.2 to 42.8% (becomes Ga rich). This phenomenon is similar to that of Jackson's *et al.* report[9] which studied n-InGaAs by using $SiBr_4$, and the consideration has to be discussed in more detail.

In conclusion, SiI_4 has been used as a new Si dopant source in GaAs and InP grown by CBE. The net carrier concentration of GaAs and InP doped by SiI_4 is comparable with previous reports using other dopants. A constant carrier concentration was obtained in a wide growth temperature range from 470 to 540 °C and a III/V ratio range from 10 to 20, so that an excellent sheet resistance of less than 2% uniformity for both n-GaAs and n-InP layers grown on 3 in. diameter was also obtained. The relation between carrier concentration and Si concentration in Si-doped GaAs by using SiI_4 and Si_2H_6, and Si-doped InP by using SiI_4 was determined and the electrical activation ratio of Si in SiI_4 for both GaAs and InP is almost 100% in the range studied, while that for Si_2H_6 is 80% or less. These satisfactory results suggest that SiI_4 is a promising candidate as a Si dopant source for CBE growth.

[1] P. J. Skevington, D. A. Andrews, and G. J. Davies, J. Cryst. Growth **105**, 371 (1990).
[2] H. Heinecke, K. Werner, M. Weyers, H. Luth, and P. Balk, J. Cryst. Growth **81**, 270 (1987).
[3] K. Kimura, S. Horiguchi, K. Kamon, M. Shimazu, M. Mashita, M. Mihara, and M. Ishii, J. Cryst. Growth **81**, 276 (1987).
[4] M. Shimazu, K. Kamon, K. Kimura, M. Mashita, M. Mihara, and M. Ishii, J. Cryst. Growth **83**, 327 (1987).
[5] H. Ando, N. Okamoto, A. Sandhu, and T. Fujii, Jpn. J. Appl. Phys. **30**, L1696 (1991).
[6] M. Weyers, J. Musolf, D. Marx, A. Kohl, and P. Balk, J. Cryst. Growth **105**, 383 (1990).
[7] C. R. Abernathy, S. J. Pearton, F. Ren, and J. Song, J. Cryst. Growth **113**, 412 (1991).
[8] Y. Horikoshi, M. R. Fahy, M. Kawashima, K. Furukawa, M. Fujino, and N. Matsumoto, Jpn. J. Appl. Phys. **33**, L413 (1994).
[9] S. L. Jackson, M. T. Fresina, J. E. Baker, and G. E. Stillman, Appl. Phys. Lett. **64**, 2867 (1994).
[10] M. T. Fresina, S. L. Jackson, and G. E. Stillman, Proceedings of the International Symposium Compound Semiconductors, San Diego, 1994, p. 699.
[11] CRC Handbook of Chemistry and Physics, 72 nd ed. (1991–1992), pp. 9–105.
[12] R. A. Hamm, S. Chandrasekhar, L. Lunardi, and M. Geva, J. Cryst. Growth **148**, 1 (1995).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 137.189.170.231 On: Fri, 19 Dec 2014 00:04:15