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Observation of Negative Differential Resistance in a $Si/Ge_{0.4}Si_{0.6}$/Boron δ-Doped Si Heterostructure

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ABSTRACT

In this paper, observation of the negative differential resistance (NDR) phenomenon in a three-terminal pseudomorphic i-Si/i-$Ge_{0.4}Si_{0.6}$/δ-doped-Si heterostructure is reported. The proposed structure offers high hole mobility of about 2650 $cm^2/V\cdot s$ at 77 K in the $Ge_{0.4}Si_{0.6}$ channel and shows a pronounced NDR property in the drain-source *I-V* characteristics. The measured onset drain-source voltage of the NDR region is found to be within a range of 0.9~1.4 V, which strongly depends on the collector voltage. Real-space transfer (RST) of light holes between the channel and collector regions is shown to be responsible for the observed NDR characteristics. Experiment results and the device operation are described. In addition, the influence of the drain-collector leakage current, due to a non-ideal undoped layer, on the NDR behavior is analyzed.

Key Words: negative differential resistance, real space transfer, GeSi heterostructure, peak-to-valley current ratio, onset voltage

I. Introduction

Real-space transfer (RST) of electrons (or holes) in semiconductor heterostructures has attracted increasing attention because adjustment of the electron distribution with respect to energy occurs very rapidly (Luryi *et al.*, 1990; Luryi, 1991; Katalsky *et al.*, 1986a, 1986b), which is very attractive for switching, microwave, and memory devices applications (Daembkes *et al.*, 1986; Patton *et al.*, 1988; Luryi *et al.*, 1986, 1990). Essentially, RST is a thermionic emission of hot carriers in a direction perpendicular to the external applied electric field for channel carrier acceleration. The main body of RST devices consist of, at least, a channel region in which hot carriers are generated, a barrier region in which cold channel carriers are confined, and a collector region in which hot carriers thermally injected over the barrier are collected.

RST in multilayer heterostructures was first postulated by Gribnikov (1973) and Hess *et al.* (1979) and subsequently realized by Keever *et al.* (1981) in a modulation-doped AlGaAs heterostructure. Since these pioneering works, a variety of experimental and theoretical studies on related devices, such as the negative resistance field-effect transistor (NERFET) and charge-injection transistors (CHINT) (Kastalsky *et al.*, 1984, 1986a, 1986b; Vinter and Tardella, 1987), have been reported in the literature. So far, experimental work on RST devices has mainly focused on III-V compounded semiconductors, such as AlGaAs/GaAs, InGaAs/GaAs, and InAlAs/InP material systems. However, the RST effect in these materials is liable to be accompanied by momentum-space (k-space) transfer due to intervalley scattering, which may significantly slow down the RST process (Kizilyalli and Hess, 1989).

With advancements in silicon molecular beam epitaxy (Si-MBE) technology, device quality strained Ge_xSi_{1-x}/Si heterostructures have now become possible. The strained Ge_xSi_{1-x}/Si heterostructure has a small light-hole effective mass, a large valence band offset, and, in particular, is free of k-space transfer due to its large intervalley separation. It, thus, offers a promising choice for the fabrication of RST devices. Most important, it opens a new era for the realization of ultra-high speed devices using Si technology.

To the authors' knowledge, Mensz *et al.* (1990) first reported observation of RST of hot holes in a strained $Ge_{0.2}Si_{0.8}$/Si heterostructure. In their structure, hot holes faced a reverse-biased *np* (collector-substrate) junction after they were thermally injected over an n-Si barrier layer. The negative differential resistance (NDR) phenomenon in the source-drain characteristics was primarily caused by the buildup of RST hot holes in the collector region, which resulted in drastic depletion of the conduction channel.

In this paper, a novel i-Si/i-$Ge_{0.4}Si_{0.6}$/δ-doped Si structure with a drift electric field developing on the barrier layer for the RST process, as opposed to use of an *np* junction, is proposed. Experimental measurements show that the proposed structure provides significant improvement in hole mobility especially at low temperatures, which is expected to lead to a better RST effect. The basic device operation principle and experimental drain-source *I-V* characteristics measured at 300 K and 77 K will be analyzed and discussed. In particular, the influence of the drain-collector leakage current on the NDR performance of the drain-source characteristics will also be investigated.

II. Experiment

A cross section of the proposed device structure is shown schematically in Fig. 1. Essentially, the present device is analogous to a p-channel FET but has a collector-up structure. The 150 Å-thick undoped $Ge_{0.4}Si_{0.6}$ layer comprises the conducting channel with carriers (holes) supplied from a close proximity boron δ-doping. The *p*-channel was chosen since most of the Ge_xSi_{1-x}/Si band offset distinctly lies in the valence band, which is favorable for hole transport (Kastalsky *et al.*, 1984).

The epitaxial layers were grown on (100) p^+-Si substrates using a Vieetech molecular beam epitaxy (MBE) system. The Si substrates were cleaned using a standard cleaning process. Before growth, *in-situ* thermal cleaning conducted for 10 minutes at 900 °C is to remove the native oxide layer from the Si substrate. The substrate was then cooled down to 500 °C for epitaxial growth of coherently strained Ge_xSi_{1-x} layers. The layer sequence consisted of an undoped Si buffer layer of 5000 Å-thickness, a boron δ-doped layer (with a sheet carrier density of 5×10^{12} cm^{-2}), followed by a 70 Å-thick undoped Si spacer, a 150 Å-thick undoped strained $Ge_{0.4}Si_{0.6}$ channel layer, and a 500 Å-thick undoped Si layer, which served as a barrier region for the RST of channel carriers.

Note that the distance between the channel layer and the boron δ-doped layer plays a crucial role in determining the number of carriers which can be transferred from the δ-doped region to the channel region at thermal equilibrium. Based on self-consistent calculations, an optimum value of 70 Å was employed here, which enabled the undoped $Ge_{0.4}Si_{0.6}$ conducting channel to have about 85% of the total number of carriers from the underneath δ-doping region in equilibrium.

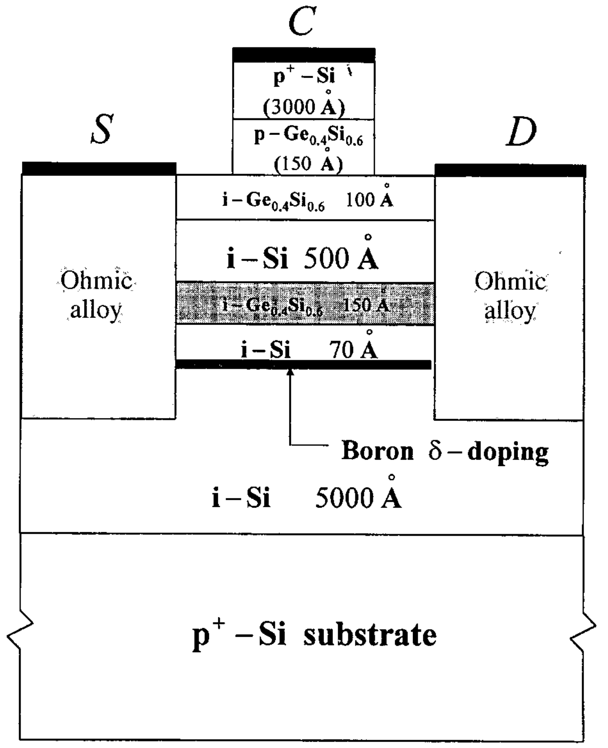

Fig. 1. Schematic cross section of the layer structure and the contact geometry of the device. The device had a collector area of 5×300 μm^2, and the drain and source space was 10 μm.

Above the i-Si (500 Å) barrier layer, in order to obtain good ohmic contact with the collector, a cap layer, consisting of a 100 Å-thick undoped $Ge_{0.4}Si_{0.6}$ spacer layer, a heavily boron doped 150 Å-thick $Ge_{0.4}Si_{0.6}$ layer, and a 3000 Å-thick p^+ (boron)-Si layer, was grown. Here, the 100 Å-thick undoped $Ge_{0.4}Si_{0.6}$ spacer layer was used to block possible out-diffusion of boron from the above p^+-$Ge_{0.4}Si_{0.6}$ layer. The 3000 Å-thick p^+ (boron)-Si capped layer not only provided a good ohmic contact with the collector metal but also acted as a potential barrier on the collector side to prevent possible hot holes from reflecting back to the channel region. Note that the background doping of the grown undoped layers was on the order of about 10^{15} cm^{-3} (n-type).

In the compressively-strained $Ge_{0.4}Si_{0.6}$ channel layer, light hole and heavy hole valence bands are split due to different mass quantization and the compressive strain. In the channel region, the light hole band lies below the heavy hole band, which results in different potential barrier heights for the RST of light and heavy holes. Following the theoretical calculation proposed by People (1986), the Ge content chosen (x=0.4) provided a RST potential barrier height of 270 meV and 339 meV for light and heavy holes, respectively. The smaller RST barrier height of the light holes along with the smaller effective mass and higher mobility of the latter, as compared to that of the heavy holes, suggests that the RST characteristics will be dominated by the light holes. It is worthy of noting that the higher Ge composition in the strained Ge_xSi_{1-x} conduction channel is preferred for study of hot hole RST properties due to the increase of hole mobility with the Ge mole fraction x. However, a compromise should be made between the Ge mole fraction and the critical thickness limitation (People, 1986; Luryi *et al.*, 1990).

Standard photolithography was used in device fabrication. Rapid thermal processing was used in all the high temperature steps to minimize the thermal relaxation of the strained $Ge_{0.4}Si_{0.6}$ layers. Device processing began with definition of the device area through deep mesa etching, followed by removal of the cap layer for drain and source contacts by means of properly controlled wet chemical mesa etching. Al was used for ohmic drain/source and collector contact metallization. The device had a collector area of a 5×300 μm^2, and the drain and source space was 10 μm.

It should be noted that various post-metal sintering conditions have been carefully investigated to obtain ohmic drain/source contacts with the conduction channel. Note that this is the most critical step during device fabrication. Improper sintering conditions may result in reach-through between the drain/source contact and the substrate. The optimum conditions obtained so far for both the drain/source and collector contacts is sintering in forming gas at 450 °C for about 10 s.

III. Results and Discussion

Due to the higher Ge content in the channel region with carriers provided by close proximate boron δ-doping, the present structure was expected to have both higher hole density and greater mobility. Based on the Hall measurement, the hole mobility and the sheet carrier density in the channel were about 2650 (830) cm^2/V·s and 1.2×10^{11} cm^{-2} (2.5×10^{11} cm^{-2}) at 77 K (300 K), respectively. Note that the hole mobility at 77 K was about 3.1 times that at 300 K. The smaller carrier density at 77 K as compared to that at 300 K might have been due to the freeze-out effect (Carns *et al.*, 1993; Wang *et al.*, 1994) of the δ-doping.

Figure 2(a) and (b) show the measured I_D–V_D characteristics under different negative collector voltages at 300 K and 77 K, respectively. The *I-V* curves were obtained using a Tektronix type 370A curve tracer. At 77 K, the fabricated device exhibited NDR behavior even when V_C=0 V (the bottom curve). Since the effective potential barrier for the RST of light holes in the $Ge_{0.4}Si_{0.6}$ could be effectively reduced by in-

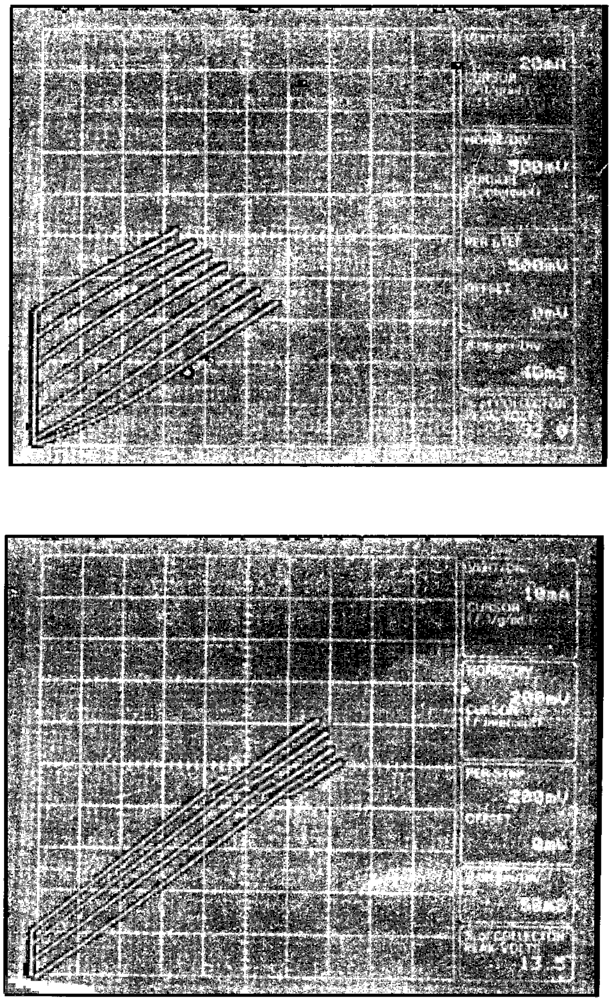

Fig. 2. Drain characteristics I_D versus V_D at various negative collector voltages at (a) 300 K and (b) 77 K. The collector voltage was increased in steps of -0.5 V and -0.2 V for the 300 K and 77 K *I-V* characteristics, respectively.

creasing the collector voltage (as will be explained later), the onset voltage of the NDR characteristics, V_γ, decreased with increasing V_C. Values of V_γ from 0.9 V to 1.3 V were observed as shown in Fig. 2(b) when V_C was increased from 0 V to -0.6 V. In general, V_γ depended primarily on both the heating efficiency of the holes in the conducting channel and the potential barrier height for the RST process.

The onset voltages for the NDR in the proposed structure occurred at elatively lower drain voltages as compared to Mensz's results (Mensz *et al.*, 1990). The reason for this may have been that (1) the use of higher *Ge* content in the conducting channel favored the heating efficiency of RST light holes, and that (2) the application of V_C and V_D resulted in a lower barrier for the RST light holes.

For the I_D–V_D curve obtained at 77 K, the hys-

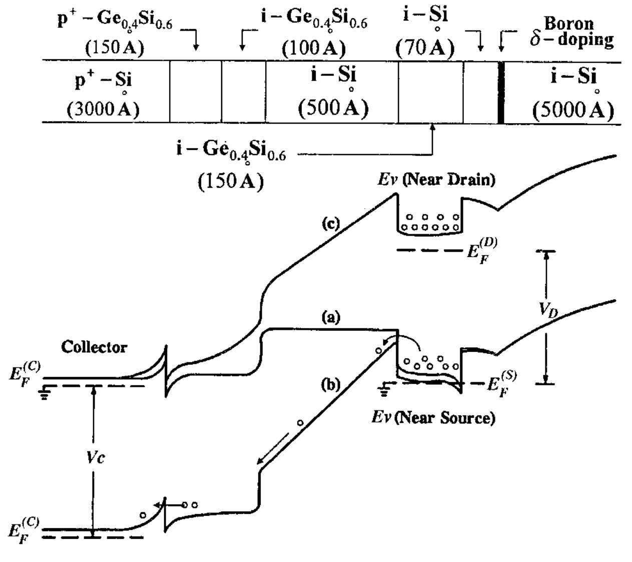

Fig. 3. Schematic valence-band diagrams of the device near the source and the drain regions under positive drain (V_D) and negative collector (V_C) biases. For convenience, the hole energy is shown as positive.

teresis within the NDR region might have arisen due to the occurrence of a switching mechanism (Kinder *et al.*, 1991) in the drain circuit.

The operation theory of the proposed structure can be qualitatively explained using the schematic hole energy band diagrams shown in Fig. 3. In this figure, for convenience, the hole energy is shown as positive, and only the light hole energy band is shown in the strained layers. The curves labeled (a) and (b) denote the energy band diagrams near the source under thermal equilibrium and under a negative V_C biased condition, respectively. The curve labeled (c) denotes the energy band diagram near the drain when a positive V_D was applied. Note that the external applied voltages V_D and V_C refer to the source electrode, which was kept at the ground potential.

For a small V_D, the device behaved just like a normally-on p-channel FET. Under low-field conditions, the gain in the kinetic energies of the light holes (along the direction perpendicular to the conducting channel) due to "effective scattering" during movement in the conducting channel was small; accordingly, the RST effect was negligible. As V_D increased, the extent od effective scattering increased, and the hole temperature, T_h (approximately proportional to the square of the heating electric field along the channel (Luryi, 1991)), increases. When T_h was high enough, thermionic emission of hot carriers from the conducting channel occurred, followed by collection in the collector electrode; as a result, an RST current began to flow in the collector electrode. This RST current can be regarded as an extraction of the drain-source current. When V_D exceeded V_γ, the RST current became sufficiently large, and the drain current I_D exhibited a significant drop; consequently, this gives rise to an NDR region in the drain-source *I-V* characteristics.

Consider now the case where a negative V_C was applied. A negative V_C created a downhill potential in the barrier region (the curve labeled (b) in Fig. 3), analogous to the Schottky effect, and the drift electric field in the barrier region resulted in a lowering of the effective RST potential barrier height. Thus, V_γ decreased with the increase of V_C. Note that for the particular case of V_C=0 V, as indicated by curve (c) in Fig. 3, a positive heating voltage V_D gave rise to a drift electric field in the barrier region near the drain, which was beneficial for the RST of the hot holes moving from the channel to the collector. The drift electric field in the barrier region near the drain was strongly enhanced when both V_C and V_D were applied simultaneously. Obviously, without such a drift electric field, especially for the case where the collector is grounded, hot carriers thermionically injected over the barrier region might have an opportunity to traverse back to the channel region, which will result in a degraded RST effect.

The present structure showed a low peak-to-valley current ratio (PVR) (~1.1) for the NDR at 77 K and no NDR behavior at 300 K. Based on the experimental measurements, it was found that the existence of a leakage current between the drain and the collector regions might have been responsible for the low PVR at 77 K. In addition, this leakage current might have been large enough to overwhelm the RST current at 300 K. The possible origin of the drain-collector leakage current might have been (1) the existence of a drain-collector conducting path and/or (2) the occurrence of partial relaxation in the strained GeSi layers. At 77 K, this leakage current inevitably degraded the PVR of the NDR characteristic. At 300 K, however, the drain-collector leakage current might have been much higher than the drain-source current, resulting in suppression of the NDR behavior in the drain-source characteristics caused by RST.

The partial relaxation of the strained GeSi layers may have resulted from the high temperature processing steps (e.g., thermal annealing of contact metal) during device fabrication. Relaxation of the strained Ge_xSi_{1-x} layers induced a significant number of interface states at the GeSi/Si heterointerface, strongly impairing device performance. Since rapid thermal processing was used in the device fabrication to reduce possible thermal relaxation, the second leakage current component should have been relatively smaller and is neglected here. The drain-collector conduction path

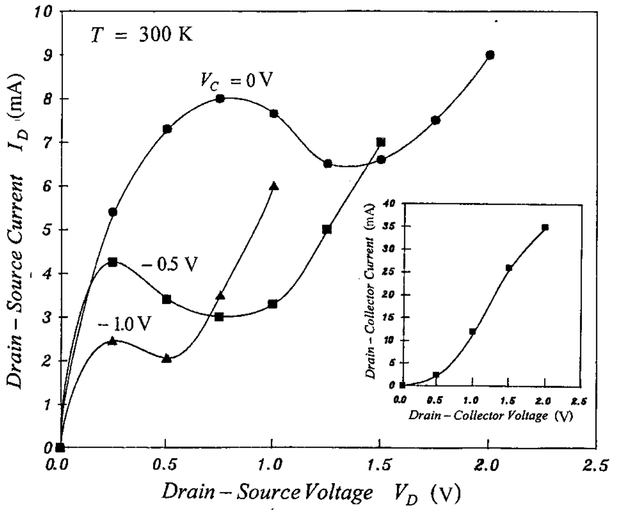

Fig. 4. The I_D-V_D characteristics after removing the drain-collector leakage current under different negative collector voltages at 300 K. The inset shows the drain-collector leakage current measured at 300 K.

may have arisen because the background carrier concentration in the MBE grown undoped Si barrier was on the order of 10^{15} cm^{-3} (p-type). Such a large drain-collector current is thought to dominate the leakage current for cases in which a negative collector voltage is applied.

To confirm the above statement, we measured the drain-collector leakage current during measurement of the I_D–V_D characteristics. By subtracting the corresponding collector leakage current (see the inset in Fig. 4) from the drain current I_D, the I_D–V_D characteristic, after removing the drain-collector leakage current at 300 K, can be determined and is shown in Fig. 4. It is very encouraging to find that the clean I_D–V_D curves show a pronounced NDR characteristic. A similar result is also found for the 77 K case but with a much stronger NDR characteristic. The onset drain voltage of the NDR in the clean I_D–V_D characteristic is also seen to decrease with an increase in the collector voltage. Based on the above analysis, it appears that a room temperature RST NDR in a Ge_xSi_{1-x}/Si heterostructures is possible once the drain-collector leakage current is reduced. Obviously, further studies on device design and process optimization are required to improve device performance.

IV. Conclusion

In summary, the observation of the NDR characteristic in a novel i-Si/i-$Ge_{0.4}Si_{0.6}$/δ-doped-Si heterostructure has been reported and explained by considering real-space hot light hole transfer. The proposed structure offers high channel conductance with high sheet carrier concentration and high hole mobility. A peak hole mobility of around 2650 cm^2/V·s and a PVR of around 1.1 have been obtained at 77 K. In addition, the origin and the influence of the drain-collector leakage current have been investigated. Our findings indicate that reduction of the parasitic current is a key factor in realizing a zoom temperature NDR based on a Si/Ge_xSi_{1-x} heterostructure. It is expected that devices with much better performance could be obtained by optimizing the layer structure and reducing the background doping of the undoped layers.

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矽鍺（$Si/Ge_{0.4}Si_{0.6}$）異質結構動態負電阻特性研究

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摘　要

本文旨在報導一種三端i-Si/i-$Ge_{0.4}Si_{0.6}$/δ-doped-Si異質結構之電特性實驗結果。此結構在77 K溫度下，$Ge_{0.4}Si_{0.6}$通道內電洞之移動率高達2650 $cm^2/V{\cdot}s$，並在0.9~1.4 V偏壓範圍內，於汲-源兩極間呈現極顯著之負微分電阻特性。實驗數據顯示通道內電洞之實空間轉移係造成微分電阻特性之主因。文中將分別對磊晶層之成長、元件之製造、*I-V*量測、以及操作原理進行說明與討論。有關集極漏電電流對汲-源兩端負微分電阻特性之影響將作深入之探討。