Impact Ionization in Strained-Si/SiGe Heterostructures

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Abstract

We have experimentally studied impact ionization (II) in a strained-Si/SiGe heterostructure. We found that, unlike bulk Si, II in this heterostructure has a *positive* temperature coefficient. Coupled with the severe self-heating that characterizes this heterostructure, this results in significantly higher levels of II when compared with reference Si devices operating under identical conditions.

Introduction

Strained-Si technology holds great promise in the continuing drive to push CMOS along the scaling roadmap [1]. Currently, research in this area is mainly focused on logic applications. However, as with all CMOS generations, there will eventually be strong interest in mixed-signal applications such as for wireless communication products. At this time, little is known about the potential of strained-Si technology for the high frequency power amplifier function. For this, impact ionization (II) is a key consideration because it ultimately determines the breakdown voltage and by extension the maximum power that a technology can deliver. II is also a significant consideration in device design for most other applications as it greatly affects device reliability.

In this work we present the first experimental study of II that we know of in this material system. Our key finding is that II in the strained-Si/SiGe system is more than an order of magnitude higher than that of bulk Si under identical operating conditions. We have found that this is the result of the interplay between the severe self-heating that occurs as a result of the low thermal conductivity of the SiGe buffer coupled with a strong *positive* temperature dependence of II in this material system. Our findings cast a cloud over the RF power potential of strained-Si/SiGe heterostructures.

Device Test Structure

Our device choice for investigating II effects in the strained-Si/SiGe heterostructure is essentially an integrated resistor with a body contact on the back side of the wafer (Fig. 1). The heterostructure was grown by UHVCVD on a p+ Si handle wafer. It is comprised of a 2 µm compositionally graded buffer followed by a 4 µm relaxed p-type $Si_{0.8}Ge_{0.2}$ layer and a 15 nm strained-Si layer on top. After the growth of the graded buffer layer, the samples received a chemical-mechanical polish (CMP) prior to the growth of the compositional layer for the purpose of reducing surface roughness. The uniform composition $Si_{0.8}Ge_{0.2}$ layer thickness and doping (2×10^{16} cm^{-3}) were chosen to prevent the n+ depletion region reaching the dislocations in the graded region and causing unwanted leakage current. The device active area was defined by an LTO deposition and etch. This was followed by surface passivation using a 4 nm thermal oxide. The active areas were then implanted with 1×10^{13} cm^{-2} 20 keV As to form the n- resistor region. Contact regions were given a high dose As implant. The process was completed by LTO deposition, an RTP spike anneal at 1000 °C, contact cuts and metallization (Ti/Al). The final resistor length is 1 µm. Bulk Si samples were processed as a reference.

The resistor resembles the n- drift region of a power device if it were implemented in this technology. In this device,

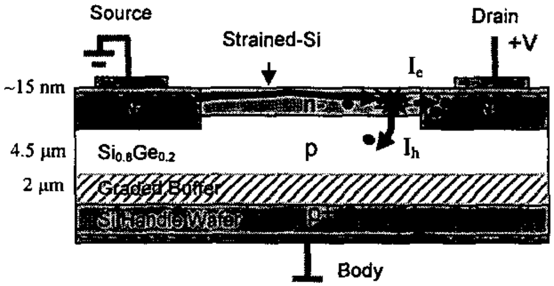

Fig 1: Cross-section of the II test structure. The hole current (I_h) produced by II is collected through the body contact.

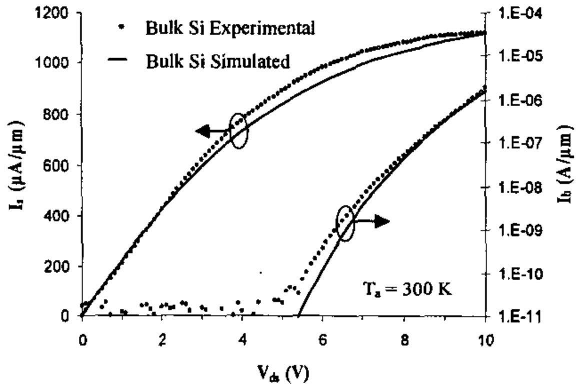

Fig 2: MEDICI simulation of the bulk Si reference test structure. The close match of the simulated and experimental data indicates that the body current is a clean measurement of II in the test structure and that surface effects do not play a significant role.

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parallel current conduction would take place through the strained-Si layer and underlying SiGe buffer layer. This is, therefore, the proper structure to study II for RF power applications. This test structure is operated with a voltage applied across the two n+ contacts. The body is kept at ground. At high enough voltages, the lateral electric field produces II events. Any generated holes are collected by the body contact and extracted as body current. MEDICI simulations of a reference Si device using the standard Van Overstraeten model for II [2] match well to the experimental I-V characteristics (Fig 2). This confirms that the body current is a clean measure of II.

Results and Discussion

I-V characteristics of the resistor taken at 300K are shown in Fig 3. The applied drain-source voltage (V_{ds}) has been corrected for the parasitic resistances of the n+ regions and contacts to give the intrinsic voltage that appears across the n-resistor region (V_{int}). The parasitic resistances were measured using Kelvin test structures. Under identical conditions, the strained-Si samples exhibit a lower high-field source current than the bulk samples. In contrast, the body current is more than one order of magnitude higher. The strained-Si/SiGe sample also shows negative output conductance indicating the presence of significant self heating. The lower high-field source current partially arises from self-heating as well as parallel conduction through the n-type portion of the underlying SiGe buffer, which is characterized by a much lower mobility [3].

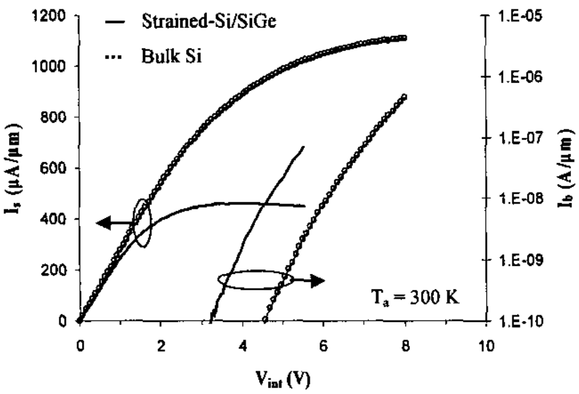

Fig 3: I-V characteristics for the strained-Si/SiGe and bulk Si test structuresas a function of the intinsic voltage (V_{int+}).

The higher body current of the strained-Si sample is indicative of higher impact ionization as measured by the II multiplication coefficient, M-1=I_b/I_s. M-1 is a useful figure of merit to gauge the extra current generated by II. As seen in Fig 4, for the same average lateral electric field (E_{avg}), M-1 in the strained-Si/SiGe devices is close to two orders of magnitude higher than in the bulk Si sample. Further evidence of enhanced II in the strained-Si/SiGe samples is the breakdown voltage, which is nearly 4 V lower than in the bulk Si samples (Fig. 5). In order to ensure repeatable measurements of II for all conditions, the maximum voltage applied to the devices was kept well below the breakdown voltage. The II was not found to change with the body voltage (V_{bs}), and all measurements shown are for V_{bs} = 0 V.

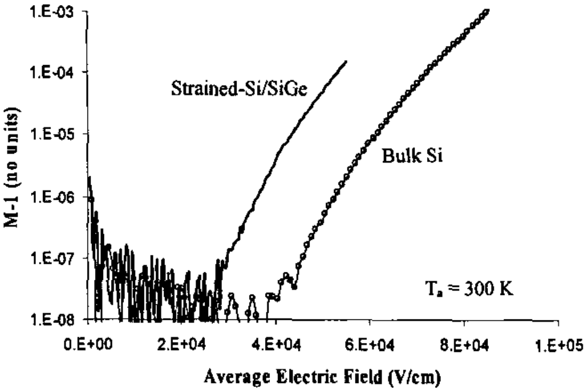

Fig 4: M-1 vs. Average lateral electric field for the strained-Si/SiGe and bulk Si test structures.

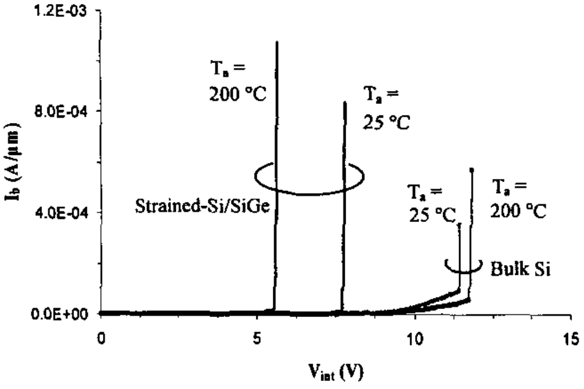

Fig 5: I_b vs. V_{int} for the strained-Si/SiGe and bulk Si samples biased to breakdown. The strained-Si/SiGe test structure has a much sharper breakdown than bulk Si and also breaks down about 4 V earlier when compared to room temperature. At 200 °C the breakdown voltage of the bulk Si samples increases slightly but decreases by 2 V for the strained-Si/SiGe samples.

Figs. 6 to 8 show the temperature dependence of the source and body currents and II for both structures. In both cases, the saturation current decreases with increasing temperature (Fig. 6) indicating enhanced phonon scattering at elevated temperatures. Interestingly, II in the strained-Si/SiGe sample exhibits a strong positive dependence on temperature, which is opposite to what is seen in bulk Si (Figs. 7,8). The positive temperature dependence of the II is also apparent in the breakdown performance of the devices. At 200 °C the breakdown voltage of the strained-Si/SiGe devices decreases by 2 V; whereas, it increases by 0.3 V for the bulk Si samples (Fig. 5).

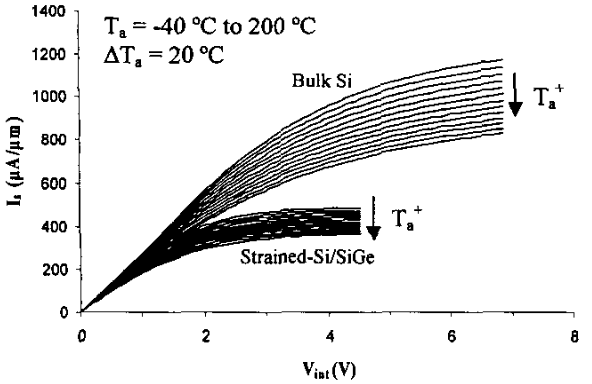

Fig 6: I_s vs. V_{int} for the range of ambient temperatures between -40 °C and 200°C. T_a^+ indicates the direction in which the temperature is increasing. As expected, both the strained-Si/SiGe and bulk Si samples show reduced current for increasing temperature indicating enhanced phonon scattering.

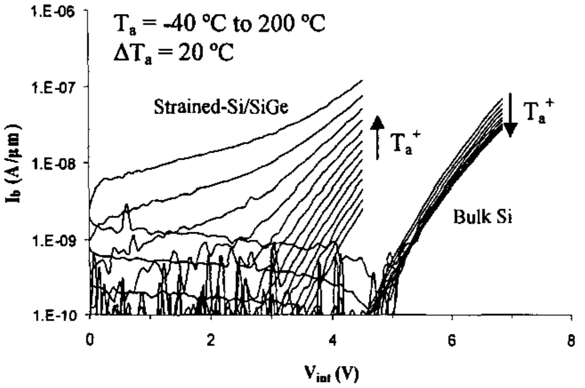

Fig 7: I_b vs. V_{int} for the range of ambient temperatures between -40 °C and 200°C. The strained-Si/SiGe sample exhibits a strong positive temperature dependence in contrast to bulk Si, which has a much weaker negative dependence. Leakage current in both structures increases at higher temperatures.

In order to make a proper comparison of II in the strained-Si/SiGe heterostructure and bulk Si, self heating needs to be accounted for. Towards this end, we have carried out pulsed measurements (Fig. 9) at different ambient temperatures. The slope of the line constructed from the intersection points of the pulsed I-V curves with the static curve (Fig. 10) versus the static power yields the thermal resistance of the sample. Using this method, the thermal resistance of these devices was estimated to be 170 µm.K/mW. The thermal resistance of a structure with a thinner $Si_{0.8}Ge_{0.2}$ layer of 2 µm was found to be the same. This compares well to the value of 134 µm.K/mW found by Jenkins for a 1.5 µm buffer [4]. These results suggest that for our thick buffer layers, the main heat losses take place through the wafer's top surface. In our experiments, the power levels are such that large temperature increases take place. A device operating at an ambient temperature of 25 °C can rise up to over 400 °C.

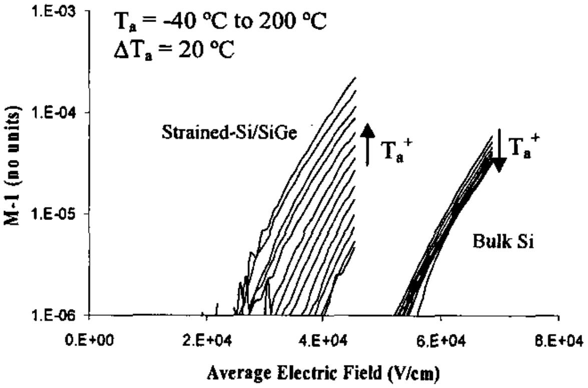

Fig 8: M-1 for the range of ambient temperatures between -40 °C and 200 °C. The leakage current seen at higher temperatures in Fig. 7 was factored out of I_b before the M-1 extraction was made. The positive temperature coefficient of II in the strained-Si/SiGe is evident.

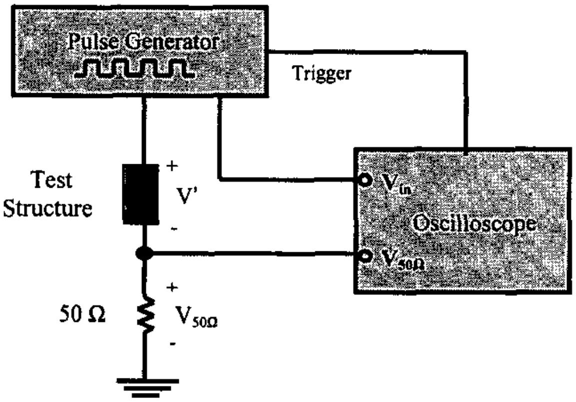

Fig 9: Schematic of the pulse setup used to measure self heating effects in the strained-Si/SiGe test structures. A pulse is applied to the drain of the device through a 50 Ω terminated probe (V_{in}). A 50 Ω resistor is connected between the source and ground and the voltage across it measured ($V_{50\Omega}$). Thus, V' = V_{in} - $V_{50\Omega}$ and I_s = $V_{50\Omega}/50$.

Using the extracted value of thermal resistance, II isotherms can be reconstructed from the static DC measurements taken over a wide range of temperatures (Fig. 11). At a given E_{avg}, the temperature dependence of II is found to be exponential (Fig. 12). At higher temperatures, the II dependence on E_{avg} becomes compressed.

II in SiGe has previously been experimentally studied by means of photodiodes [5]. Theoretical Monte Carlo simulations of II in strained-Si have also been carried out [6]. Both studies show an increase in the impact ionization coefficient over that of bulk Si. However, to our knowledge, a positive temperature coefficient (TC) for II has not been predicted for strained-Si. However, this is not an entirely surprising result. In the $In_xGa_{1-x}As$ system, the temperature coefficient of II changes from being negative for GaAs (x=0) to becoming positive for InAs (x=1) at a composition around x=0.4 [7]. This is now understood to reflect a competition between the temperature dependence of the mean free path and that of the energy bandgap. As x increases in the $In_xGa_{1-x}As$ system, the mean free path gets longer, because the effective mass is reduced, but the bandgap shrinks. Both effects contribute to a rapid increase in the II rate. At the same time, the TC of II goes from being negative to becoming positive. This is a consequence of the dominance of the temperature-shrinkage of the bandgap over the reduction in the mean free path, which is already very long. It is, therefore, not surprising that a similar effect occurs in strained-Si where, with respect to bulk Si, the bandgap is narrower [8], the electron effective mass is smaller, and the mean free path is longer [9].

A positive TC for II has very significant implications in device applications, particularly in RF power applications. First, as the II rate increases with temperature, high temperature reliability at high voltages becomes a critical consideration. Second, as temperature increases, the breakdown voltage decreases. This limits the power handling ability of the technology. The situation is more severe in the case of the strained-Si/SiGe system because of the poor thermal conductivity of the SiGe buffer. This greatly enhances the overall II rate under a given set of conditions.

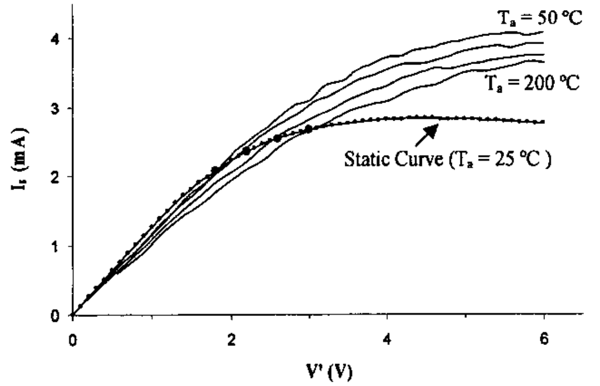

Fig 10: Comparison of the pulsed I-V curves of the strained-Si/SiGe measured at 50 °C, 100 °C, 150°C and 200 °C to the static curve measured at 25 °C.

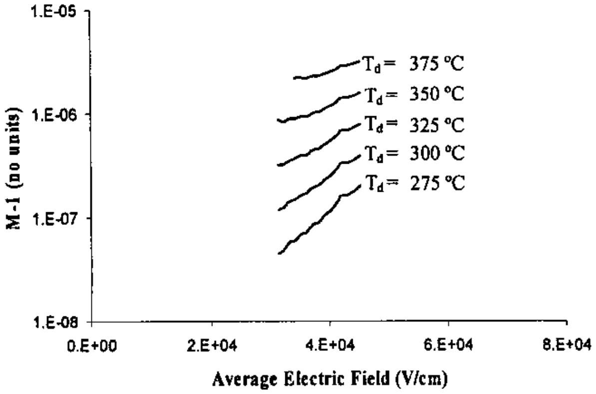

Fig 11: II isotherms for strained-Si/SiGe structure reconstructed from static DC curves measured at ambient temperatures from -40 °C to 200 °C. Curves have been labeled with estimated device temperature (T_d).

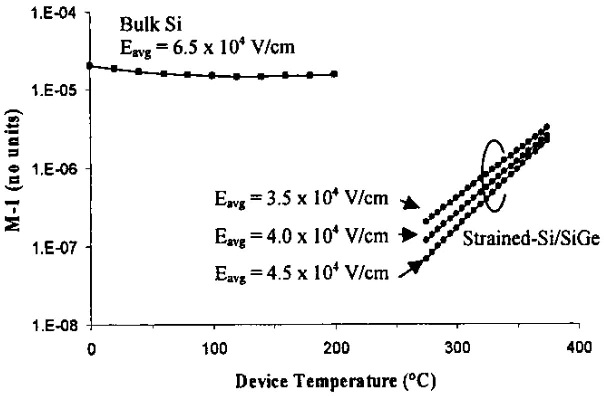

Fig 12: Plot of II in the strained-Si/SiGe test structure at different E_{avg} as a function of temperature. A plot of Si data at $E_{avg} = 6.5 \times 10^4$ V/cm is shown for reference. II in strained-Si/SiGe exhibits an exponential dependence on temperature. This implies that the temperature dependence of the bandgap is the dominant mechanism contributing to the positive TC of II.

Conclusion

We have shown that II in the strained-Si/SiGe system has a positive temperature dependence. When combined with severe levels of self-heating in the structure, we have demonstrated that the positive TC of II results in significantly higher levels of II being observed in strained-Si/SiGe devices operating at the same ambient temperature as reference bulk Si devices.

Acknowledgements

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