Discovery of a photoresponse amplification mechanism in compensated PN junctions
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Signal amplification is a fundamental process for all electronic and optoelectronic systems. The underlining physics of any signal amplification mechanisms is built upon the complex interactions among electrons, photons, phonons, and excitons. Improved understanding of these physical processes has spurred the enhancement of the quality of the obtained signals and fueled the development of new generations of electronic and photonic devices for communications, computation, imaging, and photovoltaics.1–8

Broadly speaking, signal amplification can be divided into two groups—an external process that uses transistor amplifiers and an internal process that uses the intrinsic material properties to amplify the signals. The best sensitivity or the highest signal-to-noise ratio has usually been obtained from the combination of the two amplification mechanisms. While recent works on nano-injection9,10 and multiple exciton generation (MEG)11,12 shed light on alternative internal amplification mechanisms, avalanche multiplication due to impact ionization remains to be the primary internal mechanism for signal amplification in semiconductors to date. Therefore, most of the state-of-the-art photoreceivers for telecommunications and single-photon avalanche diodes (SPADs) for quantum communications and imaging have adopted the impact ionization mechanism.13–20

However, impact ionization usually requires high bias voltage, typically 30–200 V depending on the applications and the semiconductor materials, and often suffers from high excess noise associated with the avalanche process. Because of the very high operation voltage, avalanche multiplication by impact ionization is incompatible with the mainstream complementary metal-oxide-semiconductor (CMOS) process, and imposes serious limits on the power consumption and the level of integration.

In this letter, we report the experimental observation of an internal carrier multiplication process in silicon, the most important and commonly used semiconductor material. We found that the observed gain only occurs in heavily compensated silicon p-n junctions where each side of the p-n junction contains a significant amount of counter impurities (i.e., the n-side has a significant amount of acceptors and the p-side has a significant amount of donors). At a bias level more than an order of magnitude lower than the threshold voltage for impact ionization, we observed amplified photoexcited signals well beyond the conventional photoresponse limit that one photon produces at most one electron-hole pair. By investigating the device characteristics under different temperatures, we further demonstrated that the photocurrent increases with the bias voltage and with the temperature. In contrast, conventional silicon p-n or p-i-n diodes exhibit neither the gain behavior nor the temperature dependence that is present in our device. Such photocurrent measurements reveal the physical origin of the observed gain mechanism (not restricted to silicon) involving interactions among electrons and holes in the extended states and localized states as well as electron-phonon interactions.

Figures 1(a) and 1(b) show the designs and the secondary ion mass spectroscopy (SIMS) analysis of two silicon p-n structures; we used to study the signal amplification mechanism. Sample A was formed by OMCVD (organometallic chemical vapor deposition) epitaxial growth, and...
The formed junction depth is around 100 nm, as confirmed by the SIMS profile. The in situ grown sample (sample A) was grown by an epitaxial vendor. To form the structure for sample B, phosphorous was introduced via proximity diffusion at 950°C for 35 s in a rapid thermal annealing (RTA) furnace using the phosphorous containing spin-on-dopant (SOD) as the dopant source. The formed junction depth is around 100 nm, as confirmed by the SIMS profile. Individual p-n junction devices on the OMCVD and diffused samples were formed by inductively coupled plasma reactive-ion etching (ICP-RIE) with C4F8 and SF6 gases. Each device mesa has an area of 35 μm × 55 μm and is 350 nm deep. After the mesa etch, a thin layer of SiO2 ~ 250 nm was deposited and patterned lithographically for n- and p-metal contacts. E-beam evaporated Ti/Au was used to form the Ohmic contacts for both n- and p-layers. Typical p-n junction current-voltage characteristics were obtained from both samples. Specifically, the diffused p-n junction device has an ideality factor of 1.98 and a leakage current of 85 pA at 1 V reverse bias as shown in Fig. 2.

The photocurrent of both the epitaxially grown and the diffused devices was measured under 635 nm laser light illumination. The epitaxially grown p-n junction device exhibits the photoresponse of a standard p-n or p-i-n diode, having a nearly constant photocurrent level independent of the bias voltage. In sharp contrast, the diffused p-n junction device shows that the photocurrent increases significantly with the increase of the reverse bias voltage from 0 to −4 V, signifying signal amplification as shown in Fig. 3(a). Device simulations have shown that for both device structures avalanche multiplication due to impact ionization does not take place until ~20 to −25 V bias, whereas the experimental data from the diffused p-n junction shows that the amplification starts at a bias voltage as low as −2 V. Since the devices

FIG. 1. (a) SIMS profiles of phosphorous and boron in the OMCVD grown silicon p-n junction. (b) SIMS profiles of phosphorous and boron in the diffused silicon p-n junction. The insets of (a) and (b) show the conceptual designs of the p-n junction structures, one being an “abrupt” p-n junction and the other being “partially compensated” p-n junction. (c) Effective doping profiles (i.e., Nd-Na in n-region and Na-Nd in p-region) of the OMCVD junction. (d) Effective doping profile of the diffused junction. The insets of (c) and (d) present the doping concentration ratios R for the two samples, respectively.

FIG. 2. (a) Dark I-V characteristics of the diffused p-n junction in the absence of light illumination. A typical rectifying behavior of p-n junction is observed. The inset shows the micrograph of a fabricated p-n junction with n- and p-contacts labeled. (b) Log scale plot of the dark I-V characteristics of the same p-n junction. The ideality factor is 1.98.

FIG. 3. (a) Bias dependence of photoresponse to 635 nm laser light for both diffused and OMCVD epitaxial grown Si p-n junctions at room temperature. The OMCVD epitaxial grown sample shows the photocurrent $I_{ph}$ of a typical p-n junction whereas the diffused junction shows a rapidly increasing photocurrent with the bias voltage. (b) Bias dependence of photocurrent at various temperatures for the diffused p-n junction device with high doping compensation. (c) Comparison of the temperature dependence of photoresponse between a highly compensated Si p-n junction and a conventional Si p-i-n diode at −3 V. The photocurrent of both devices has been normalized with respect to its individual value at 160 K. (d) Average number of e-h pairs $N$ generated by an energetic carrier at different temperatures obtained from the measured data in Fig. 3(b) and the expression of gain in text.
have shown typical I-V characteristics of a normal p-n junction in the dark condition, the observed amplification behavior cannot originate from the photoconductive effect or phototransistor behavior. Furthermore, the photoreponse data show that this phenomenon exists only in the heavily compensated p-n junction but is absent in regular p-n junctions. Therefore, the distinctive signal amplification must be explained by an internal carrier multiplication mechanism that is not present in the normal p-n junctions.

To explore the phenomenon further, the bias dependence of photoreponse under different temperatures was measured. Fig. 3(b) shows that the photocurrent of the diffused junction increases monotonically with bias voltage over the entire temperature range of measurements. What is particularly interesting is that the photocurrent is increased with temperature under all bias voltages. Such characteristics can be better shown in Fig. 3(c) taking the data at −3 V as an example. For comparison, the temperature dependence of photoreponse of a conventional Si p-i-n diode is also included in the figure. To remove any effects introduced by light coupling and the experimental setup, we plot the normalized photocurrent at different temperatures in Fig. 3(c) to demonstrate the fundamentally different temperature dependence of photoreponse between the compensated p-n junction and conventional p-n junctions. For conventional Si p-n or p-i-n diodes, the photoreponse between 500 nm and 700 nm is nearly temperature independent, as shown in Fig. 3(c). However, we have found that the photoreponse of the heavily compensated p-n junction possessing amplification characteristics has shown an increased photoreponse with increasing temperature. We note that by contrast the photoreponse of an avalanche photodetector decreases with increasing temperature, because the increasing phonon scattering hinders the acceleration of carriers under the applied electric field and results in a lower probability for impact ionization.

The experimental results indicate that we have discovered an internal signal amplification mechanism in heavily compensated silicon p-n junctions. It occurred at a much lower voltage than impact ionization and had a gain that increases with temperature to favor room temperature over cryogenic operation. Based on the fact that the gain is only present in materials with significant doping concentration and doping compensation, we propose a cycling excitation process (CEP) consisting of a photoexcited carrier (electron) traversing the p-n junction to gain sufficient kinetic energy to excite an electron-hole pair whose dissociation enables the hole component to repeat the same process by traversing the junction in the opposite direction. Since such scattering and dissociation events occur with finite probabilities and the carriers suffer energy dissipation by other causes, the cycling process does not exhibit any perpetual motion behavior and renders a net steady state gain.

Next, we explain in detail how the CEP happens in response to optical excitation. Fig. 4 illustrates a pathway for cyclical e-h generations initiated by a photon absorbed in the p-region of the p-n junction, where the primary or the zeroth generation of electron-hole pair \((e_0^p \text{ and } h_0^p)\) is created. We label each electron and hole by \(e\) and \(h\) with superscripts denoting generation and subscripts (p or n) indicating location of the carrier. A symmetric case can also be made for the excitation in the n-region. The primary hole \(h_0^p\) leaves the device via the p-contact and the primary electron \(e_0^p\) moves into the depletion region of the p-n junction gliding over the energy slope and gains kinetic energy. The amount of kinetic energy acquired by the electron is determined by the built-in potential, the applied bias, and the dissipative effect of inelastic scattering by phonons or by carriers in the Fermi sea known as shake-up. For heavily doped p-n junction under low reverse bias, the width of the depletion region (20–40 nm) is comparable to the electron mean free path (~15 nm) at room temperature. Hence, the energetic electron can gain sufficient energy to excite an electron across the energy gap from an ionized acceptor \((A^+\text{)}\) in the partially compensated n-doped region. This excitation process, indicated by the vertical arrows in the n-region, generates the first generation of electron hole pair \((e_1^n \text{ and } h_1^n)\). After the excitation, both the zeroth \((e_0^n \text{ and } h_0^n)\) and first generation \((e_1^n\text{)}\) electron leave the device via the n-contact. In the meantime, the acceptor that just lost its electron may capture an electron form the valence band, and this process produces the secondary mobile hole \((h_1^n)\), which can traverse the depletion region and gain sufficient energy for a second excitation process to produce the second generation of electron-hole pair \((e_2^n \text{ and } h_2^n)\) in the p-side (depletion region or the p-region) of the junction. The hole goes to the p-contact directly and the electron will again serve as the seed for a new cycle of excitations.

Fig. 4 also shows a density of states (DOS) graph for a point in the n-region of the p-n junction. Given such excitations happen in heavily doped and compensated materials, the transition is believed to be mainly between the donor and acceptor (DA) states which could be either in the extended or local states on either side of the mobility edge of the impurity band. Thus, the transition can produce either a bound DA excitation or a pair of mobile electron and localized hole or vice versa (as shown in the DOS graph in Fig. 4, and the resultant localized electron or hole thermalizes readily to become mobile carrier contributing to the photocurrent. The
interactions between the localized electrons or holes and phonons may also explain why the partially compensated p–n junction device favors room temperature rather than cytogenetic operation (Figs. 3(b) and 3(c)). In impact ionization, the carriers in the conduction and valence bands are treated as extended waves obeying the k-selection rule (or momentum conservation), but in the disordered heavily doped semiconductors, optical transitions in the range of the indirect band gap energy in silicon are evidence of transition between localized waves,22,23 relaxing the k-selection rule. Even in bulk silicon with k conservation, the computation of the absorption spectra requires the strength of the transition matrix elements provided by the atomic orbitals.39

This process requires sufficient interband transition energy, which may be vitiated by low energy intraband dissipation processes such as phonon emission and shake-up. Thus, there exists an average number of electron-hole pairs, denoted by $X_i$ and $Y_j$, respectively, generated by the $j$-th generation hot electron and hole through the excitation process as illustrated in Fig. 5. For practical device structures, we can assume $\langle X_j \rangle = x$ and $\langle Y_j \rangle = y$. The net gain from a practical device can be written as $G_{nm} = \frac{P_p}{P_p + P_n} x + \frac{P_n}{P_p + P_n} y$ based on our analytical model (see supplementary material40), where $P_p$ and $P_n$ are the percentage of light absorbed in the p- and n-region of the device. The Monte Carlo simulations show excellent agreements with the analytical model on the mean value of gain and the relatively small spread of gain distribution, which is indicative of low excess noise compared to conventional avalanche process (see supplementary material40).

In summary, we have discovered a photocurrent amplification mechanism in heavily doped, partially compensated p–n junctions of silicon. We propose that the amplification is due to a CEP initiated by optical excitation of electron and hole which produce the back-to-back ionization processes involving at least one localized state, by virtue of the increase in kinetic energy of a carrier across the p–n junction. This process connects the presence of the heavily doped donor and acceptor compensation, the driving by optical excitation, and the assistance by heat, to produce qualitatively the observed bias and temperature characteristics. Such an effect has as its mainstay the excitation of an electron (hole) from a bound acceptor (donor) state, combined with thermal ionization, to form mobile electron-hole pair. The process explains the voltage-dependent gain and the temperature characteristics of the device. The concept of CEP, in principle, applies to other semiconductors such as GaAs and other compound semiconductors where excessive amount of dopants produce self-compensation (e.g., excessive amount of Si dopants in GaAs may take both the donor and acceptor positions). Since the initial carrier may be created by photoexcitation or electrical injection in a properly designed structure, the signal amplification effect can potentially be incorporated into various kinds of devices including photodetectors and field effect or bipolar transistors. Although more detailed investigations are desirable to further understand the characteristics of the process, we believe the discovery is highly significant because of its broad potential applications for communication, imaging, sensing, and computing in which signal amplification is necessary and ubiquitous.

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40See supplementary material at http://dx.doi.org/10.1063/1.4904470 for details about the analytical analysis and Monte Carlo simulations of the photoresponse amplification mechanism.