

Silicon Based Impact Ionization Current Amplifier Integrated with External Photodiode

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Abstract

An innovative current amplification methodology, fabrication, and measurement results are reported. The basis of operation for this stand-alone amplifier is impact ionization. The device was built in silicon using standard microelectronics processes. Testing was performed by connecting the device to indium-gallium-arsenide photodiodes. Current gains above 100 along with pre-amplified leakage currents of less than 1 nA were measured.

Keywords: Impact ionization, avalanche photodiodes (APDs), low bandwidth semiconductors.

1. Introduction

The process of impact ionization in semiconductors has been well studied and quantified [1]. The phenomenon has been utilized to achieve current gain in a variety of semiconductor devices [2] [3], notably avalanche photodiodes (APDs) [4]. APDs perform a dual function of converting photons into detectable electron-hole pairs and amplifying electrical current through impact ionization [5] – significant because APDs are able to achieve lower noise gain than transistor based amplifiers, especially for miniscule currents [6]. The characteristics of the gain mechanism (noise, voltage and temperature sensitivity, frequency response, etc.) vary greatly with different semiconductors and are dependent on ionization probabilities for both electrons and holes in a given material [7] [8]. In general, silicon has the most desirable ionization properties of any semiconductor [9]. To this end, great lengths have been made to try and directly integrate silicon with other semiconductors to combine silicon's impact ionization mechanism with desirable physical properties of another semiconductor. APDs can again be cited as an example [10] [11], specifically those intended to utilize silicon gain regions and indium-gallium-arsenide (InGaAs) absorbing regions for near-infrared light collection.

In the context of the preceding paragraph, this paper presents a stand-alone amplifier based on the impact ionization gain mechanism. This device is designed to operate in conjunction with an independent current source with the two linked together by a current conducting wire. This design differs from past implementations of semiconductor devices utilizing impact-ionization gain in that those devices are integrated on the same substrate and essentially required a current generating region and an amplification region to be intimately connected. Any junction between these regions also must be depleted of mobile carriers to avoid recombination of carriers being injected from the current generating region into the amplification region. The creation of a stand-alone impact ionization amplifier frees up these restrictions imposed upon device operation. Amplifier and current sources can be designed and optimized independently including using different semiconductors for each function without concern for lattice matching, heterojunctions, or fabrication compatibility. The first clear application, and the one that has driven this development, is the integration of such an amplifier with an external photodiode current source. An attractive implementation is an amplifier made from silicon providing low-noise gain and connected to a photodiode constructed from a low bandgap semiconductor providing infrared light absorption. Such low bandwidth semiconductors usually display poor impact ionization characteristics. By combining them with an independent silicon ionization amplifier however, the result would be light detection sensitivities comparable with the best all-silicon APDs, but at optical wavelengths well above silicon's absorption cutoff.

2. Experiment

The operation principle of the impact ionization amplifier presented here is based on establishing a high electric field region vertically into a semiconductor and then injecting carriers horizontally into this region. The specific incarnation we have

fabricated uses reverse biased $N^+ - P^- - P^+$ doping regions in silicon to establish the necessary electric field. An external current source is then connected to a Schottky metal-semiconductor contact to the side of the high-field region. This amplifier is then a three terminal device. Figure 1 illustrates its essential features with a photodiode represented as the current source. In operation, the highly doped P^+ substrate is grounded and a negative voltage in relation to this ground is applied to the photodiode, reverse biasing it. A contact to the heavily doped N^+ region is then biased positively in relation to ground. As this voltage is increased, the electric field increases between the N^+ region and grounded substrate in the vertical direction. Increasing voltage also increases the depletion width in the P^- semiconductor in the horizontal direction surrounding the N^+ region. At a critical voltage, this depletion width reaches the Schottky contact and electrons can be injected into this depletion region and consequently into the high vertical electric field. Significant to the correct operation of the amplifier is the choice of dopings for the P^- layer and spacing between the Schottky contact and N^+ region. Ideally, when the critical depletion voltage is reached, the vertical electric field in the $N^+ - P^- - P^+$ region is already near avalanche breakdown so as to create significant gain. Otherwise, if large voltage increases are still required for gain, there is a danger of producing avalanche breakdown between the Schottky contact and N^+ region along the top surface of the device which is undesirable.

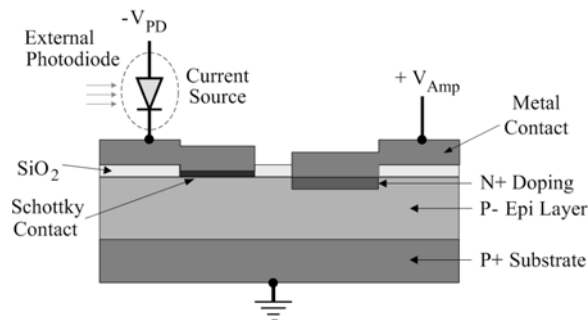


Fig. 1: Cross-section view of impact ionization amplifier illustrating its basic features. A reverse biased photodiode is connected as a current source. The high electric field is created by reverse biasing the $N^+ - P^- - P^+$ layers vertically.

Key to the operation of the device is the simultaneous vertical and horizontal flows of electrons and holes and isolating the impact ionization gain process to the vertical direction. In this way, holes created during ionization are directed towards the P^+ substrate instead of back towards the current source, which would result in carrier recombination and gain

suppression. The desire to avoid recombination also explains the use of the Schottky contact as an injection point as opposed to a doped semiconductor region.

Discrete amplifiers were fabricated using silicon wafers produced by Montco Silicon Corporation consisting of an approximately $3 \Omega\text{-cm}$ p-type epitaxial layer grown approximately $4 \mu\text{m}$ thick on a $0.01 \Omega\text{-cm}$ p-type substrate. A 300 nm layer of silicon dioxide was thermally grown on the surface in a tube furnace with an oxygen atmosphere. A $10 \mu\text{m} \times 10 \mu\text{m}$ window was opened in the oxide and phosphorous doped spin-on-glass applied. The wafers were placed in a tube furnace for 90 minutes at 1000°C to produce the highly doped N^+ region required for the device. It is estimated that this phosphorous doping layer extended $1 \mu\text{m}$ below the wafer's surface. After stripping off the spin-on-glass, another $3 \mu\text{m} \times 1.5 \mu\text{m}$ window was opened in the surface oxide and a 140 nm thick nickel layer evaporated directly onto the silicon surface. The nickel was then patterned to cover only the window opening and served as the Schottky contact for the amplifier. The spacing between the Schottky contact and N^+ region was varied between 3 and $9 \mu\text{m}$ for different devices on the same substrate. A 700 nm layer of aluminum was then evaporated onto the surface and patterned to form both the contact to the N^+ silicon region and to the nickel layer. Finally, the wafer was annealed in a tube furnace with a forming gas (N_2/H_2) environment for 5 minutes at 450°C to produce a low resistance contact between the aluminum and N^+ silicon region as well as to produce a nickel silicide at the Schottky contact interface.

Amplifiers were then evaluated when connected to external current sources, specifically InGaAs photodiodes. An HP4156 Parameter Analyzer was used to bias the amplifier and photodiodes as shown in Figure 1 with the connection between the photodiode and Schottky contact made using a microprobe and copper wire.

3. Results and Discussions

Figure 2 gives the current through the N^+ region of the amplifier versus voltage applied on the N^+ region when connected to an InGaAs photodiode. The photodiode is reversed biased to -4 V and illuminated with a $1.55 \mu\text{m}$ wavelength laser.

As indicated in Figure 2, at 75 V bias there is a large change in the current through the amplifier – this corresponds to the point where the depletion width out from the N^+ region reaches the Schottky contact ($\sim 5 \mu\text{m}$ in this case) and current can be injected horizontally into the high vertical electric field. Given the doping of the P^- layer and the voltage indicated on the figure, the calculated depletion width corresponds

well to the known spacing between the Schottky contact and N^+ region. Although the response curves are not shown here, tests of amplifiers with different spacing between the Schottky contact and N^+ region revealed different depletion voltages that correlated with this spacing.

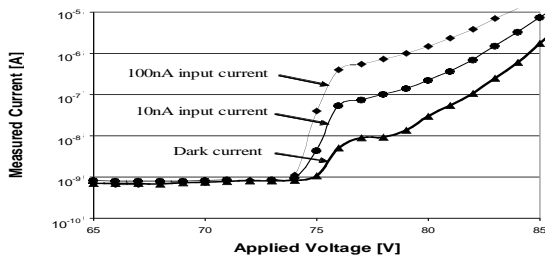


Fig. 2: Current versus voltage measurements at the N^+ region of the impact ionization amplifier when connected to external InGaAs photodiode. The photodiode is illuminated with 1.55 μm laser.

A critical figure of merit for this amplifier is its gain efficiency defined as $\text{Gain Efficiency} = \text{Injection Efficiency} \times \text{Current Gain}$, where injection efficiency describes the percentage of carriers that are successfully injected from the current source into the amplifier and current gain is the multiplication factor of the injected current in the impact ionization gain region. To calculate gain efficiency from the plots in Figure 2, dark current through the amplifier is subtracted from the total current when a photodiode is illuminated and the result is divided by the known photocurrent produced by the photodiode (as measured through the Parameter Analyzer). Figure 3 shows a plot of Gain Efficiency versus voltage on the amplifier when connected to the InGaAs photodiode producing 10 nA of current. The plots in Figures 2 and 3 indicate that very high injection and gain efficiencies are possible for this amplifier.

The impact ionization amplifier described here opens up many new possibilities for improved device design and system performance especially for optoelectronic communications and extreme sensitivity detection applications. Large numbers of these amplifiers could be fabricated on silicon substrates using processes compatible with current VLSI technology – also allowing for direct integration with subsequent transistor based amplifier and logic circuitry. Beyond the initial demonstration described here, future work will include characterization of noise, temperature sensitivity, ac frequency response, and continued optimization for low leakage current operation.

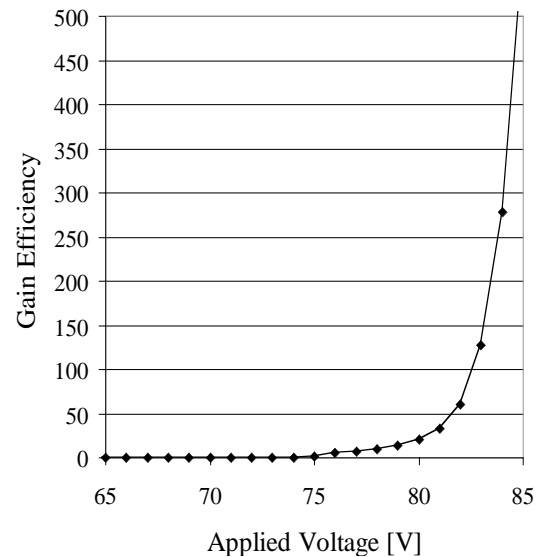


Fig. 3: Gain efficiency versus applied voltage at the N^+ region of the impact ionization amplifier with 10 nA injection current from an external InGaAs photodiode.

4. Acknowledgments

We would like to acknowledge stimulating discussions and support from Mike Jack, Ken Kosai, and John Edwards at Raytheon Visions Systems in Goleta, CA.

5. References

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