A photon detector with very high gain at low bias and at room temperature

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We report on a photon detector aimed at low light detection, which is based on the combination of small sensing volumes and large absorbing regions. Fabricated devices show stable gain values in the range of 1000–10 000 at bias voltages of ~1 V at 1.55 μm at room temperature. Submicron devices show dark current less than 90 nA and unity gain dark current density values less than 900 nA/cm^2. The noise equivalent power (NEP) is measured to be 4 fW/Hz$^{0.5}$ at room temperature without any gating, which is similar to NEP of current InGaAs/InP avalanche photodetectors in gated operation. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2802043]

Extremely sensitive detectors with high signal to noise ratio are required in a wide range of applications such as biophotonics,[1] homeland security,[2] nondestructive material inspection,[3] and quantum key distribution.[4] To satisfy this growing need, significant amount of research has been devoted to single-photon detection. In single photon detection systems, semiconductor based avalanche photodetectors (APDs) have been widely utilized due to their small footprint and ruggedness. Furthermore, APDs based on InGaAs/InP have been commonly used in near infrared spectrum: they provide stable gain values of less than two hundred and have typical unity gain dark current densities (dark current density divided by the gain) more than 10 μA/cm^2 at room temperature.[5,6] However, despite their advantages, APDs are quickly becoming the bottleneck in many applications due to their limited stable gain,[7] low quantum efficiency,[8] high excess noise,[9,10] and long deadtime.[11] These problems have pushed researchers to find alternative detection methods based on superconductors[12] and quantum dots.[13] Although superconductor based single photon detectors (SPD) can potentially solve a large number of problems associated with avalanche-based SPDs, they usually require cryogenic cooling to temperatures below 4 K, which prevents their practical utilization.

We present an alternative single photon detection method with high sensitivity. To quantify sensitivity, we used gain, dark current, and noise equivalent power as figures of merit. The gain was measured using calibrated illumination, and calculated by dividing the number of photogenerated electrons by the number of absorbed photons. Noise equivalent power was calculated using these merits and the measured noise power. Providing both high efficiency and sensitivity at room temperature is a condition that is very difficult to achieve in conventional photon detectors. The energy of a single photon in the visible or short infrared is extremely small, less than one attojoule, and the only reliable way of detecting this small energy is to use a very small volume such as a quantum dot. However, the wavelength of light is significantly larger than such a sensor, and hence the interaction between the photon and the sensor, or quantum efficiency, is extremely small.[14] We solved this dilemma by using a large-scale absorbing volume and a nanoscale sensing element, called the "nanoinjector." Figure 1 shows the operating principle for the device. Upon absorption, photons generate electron-hole pairs in the large absorption region. The electrons and holes are separated by the internal electric field of the device. Holes are attracted to the nanoinjector, which has a type-II band alignment [Fig. 1(b)], and presents a potential trap for holes. A single photogenerated hole in the absorption region is equivalent to a charge density of 1.4

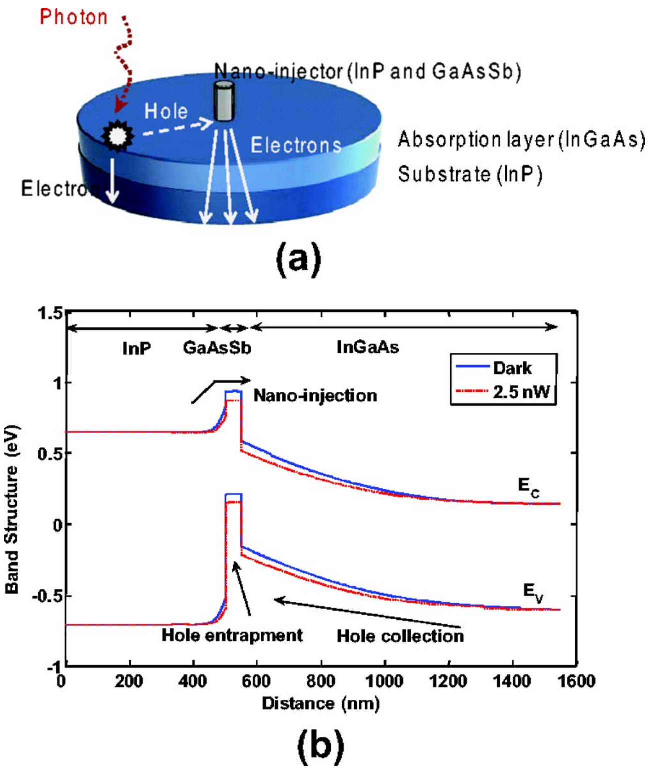

FIG. 1. (Color online) The detector concept. (a) Schematic of our semiconductor based single photon detector showing the large absorption region and the nanoinjector. The ultra small volume of the hole trap makes the device sensitive to a single charge. (b) The band structure along the central axis showing the collection and entrapment of holes as well as the electron injection.

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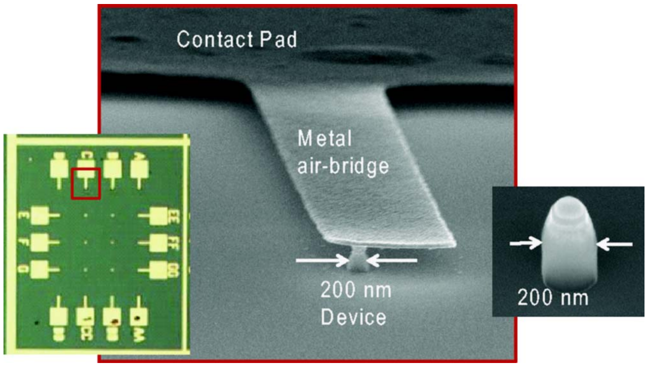

FIG. 2. (Color online) Scanning electron microscope (SEM) images of the device at different processing stages. The inset shows the nanoinjectors formed after etching. The main SEM image shows the processed device with the metal bridge that connects the top of the buried nanoinjector to a large metal pad.

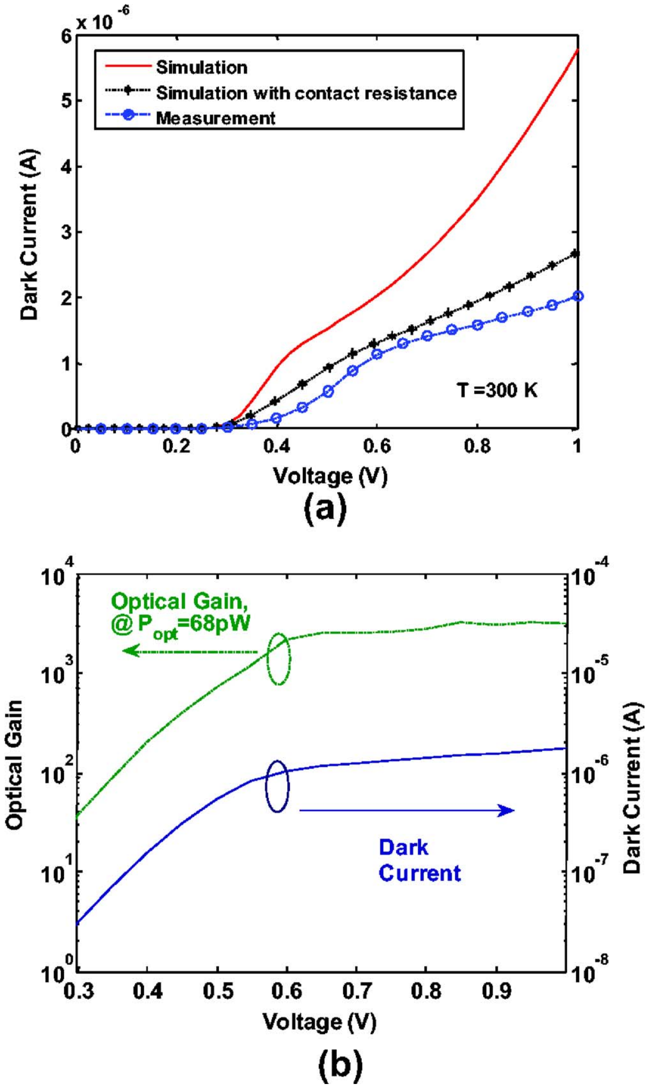

FIG. 3. (Color online) (a) Measured and modeled dark current of a device at room temperature show good agreement. All model parameters were obtained from published literature. (b) Measured dark current and gain of a 30 μm device with 5 μm nanoinjector diameter at room temperature and for an illumination power of 10 nW at $\lambda = 1550$ nm. The gain is almost independent of the optical power below 10 nW.

$\times 10^{-3}$ C/m^3. However, when trapped inside the 50 nm high and 100 nm wide diameter nanoinjector, the same hole creates an effective charge density of more than 400 C/m^3. Therefore, the impact of the hole increases by more than five orders of magnitude. Equivalently, the small volume of the trap represents an ultralow capacitance, and hence the entrapment of a single hole leads to a large change of potential and produces an amplified electron injection, similar to a single electron transistor. Our detailed simulations show that a single hole can alter the potential barrier by more than 52 mV. This is significantly higher than the thermal fluctuation energy of carriers at 300 K, and hence a high signal to noise ratio is possible even at room temperature. Furthermore, the multiplication mechanism is purely applied to one carrier, so the excess noise factor can be very small.

We used a custom developed three-dimensional simulation tool to design the epitaxial layer thickness, doping level, and composition.[15] Different types of devices were fabricated with sizes ranging from 100 nm to 400 μm. Epitaxial layers were grown on 2 in. InP substrates using metal organic chemical vapor deposition. The layer thickness and composition from bottom to top was 1000 nm of $\mathrm{In_{0.53}Ga_{0.47}As}$, 50 nm of $\mathrm{GaAs_{0.52}Sb_{0.48}}$, and 500 nm of InP. Wafers were patterned with e-beam lithography to form different size pillars. The process consisted of dry etching with $\mathrm{CH_4/H_2}$ in a reactive ion etcher, followed by wet etching with sulfuric acid and hydrogen peroxide. Samples were planarized with polyimide to help form reliable top contacts to the submicron features (Fig. 2). Conventional metallization with an e-beam evaporator was used to form the multilayer metal contacts.

Fabricated devices were tested using a computerized setup. The measured dark current showed good agreement with the simulation results, despite its not being fit to any parameters [Fig. 3(a)]. Measurements indicated that the gain increases with the bias: beyond ~1 V, a stable gain of more than 10 000 was measured for 30 μm devices with 10 μm diameter nanoinjector, and a gain of 1000 for devices with 500 nm nanoinjector [Fig. 3(b)]. 30 μm devices with 10 μm nanoinjector showed dark current values around 1–2 μA, whereas devices with 500 nm size nanoinjector had less than 45 nA of dark current. The dc measurements yielded a unity gain dark current density of less than 900 nA/cm^2 at 1 V. The gain of existing avalanche-based detectors show an exponential relation to the bias, and hence controllable gain values are limited to several hundreds.[5] In contrast, our devices show more than an order of magnitude higher stable gain, and much better tolerance to variations in voltage bias.

The noise performance of the devices was also evaluated. Spectral noise power density, dark current, and calibrated optical response of the devices were measured using a shielded high frequency probe. Using this data, the noise equivalent power was determined as 4 fW/Hz$^{1/2}$ at a gain of more than 4000 at room temperature for a device with 5 μm nanoinjector. The noise equivalent power value is similar to InGaAs/InP based APD detectors in gated operation, while our device shows higher stable gain values and requires much lower bias voltages.

The spatial response of the device was measured using a surface scanning beam with ~1.5 μm diameter and 10 nm step resolution. Despite such a high gain, the device shows a very uniform spatial response, as shown in Fig. 4. We believe that the low internal electric field in our devices is the main reason for the observed uniformity. The measured response decreases rapidly beyond a radius of about 8 μm, in com-

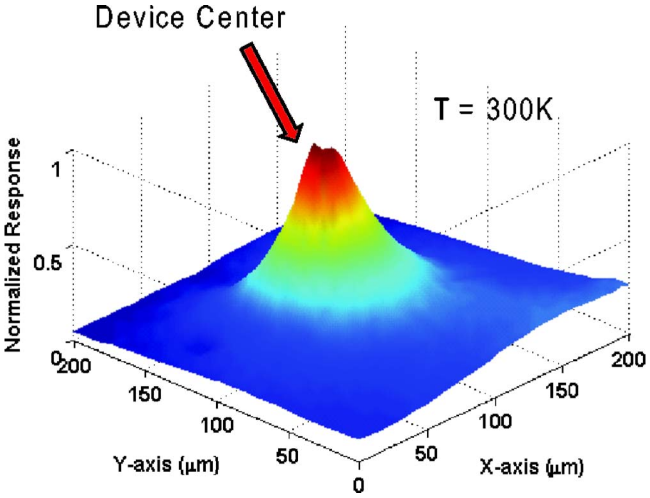

FIG. 4. (Color online) Spatial photoresponse of the device shows uniform responsivity up to a radius of nearly 8 μm, beyond which the response decreases exponentially.

plete agreement with our model. This property suggests that two-dimensional arrays of such detectors might not necessarily need pixel isolation methods such as ion implantation or mesa etching.

We have fabricated and tested a photon detector with a micrometer-sized photon absorbing volume and nanometer-sized electron switch. The devices show stable gain values exceeding several thousands, and unity gain dark current density values of less than 900 nA/cm^2 at about 1 V at room temperature. Compared with the existing APDs at similar wavelength and temperature, the results show improvement in dark current density, higher stable gain, and significant tolerance to variations in the bias voltage. The underlying concept, in principle, can be used to produce high performance photon detectors with cutoff wavelengths from the UV to far infrared.

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