An InGaN/SiNx/Si Uniband Diode Photodetector

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A novel self-powered InGaN/SiNx/Si uniband diode photodetector (PD) is introduced. The full band structure is first constructed from the transition of direct tunneling to Fowler-Nordheim tunneling of holes through the ultrathin SiNx interlayer at forward bias in the dark. Basis is the alignment of the n-InGaN conduction band with the p-Si valence band at zero bias. Under illumination, the photocurrent, responsivity, and bandwidth for the self-powered PD at zero bias indicate two distinct operation modes (i) for longer and (ii) for shorter wavelengths of incident light. The two modes involve (i) absorption in Si and electron tunneling through the SiNx interlayer and (ii) absorption in InGaN and hole transport across the SiNx interlayer. The noise is considerably larger in operation mode (i) than in operation mode (ii). This is attributed to the presence or absence of energy barriers for electron and hole transport in PD operation. Hence, noise is introduced as an independent parameter to discriminate between longer and shorter wavelength regions in dual-wavelength photodetection.

1. Introduction

Photodetectors (PDs) convert optical radiation into an electrical signal, measuring the optical power in a certain wavelength range.[1,2] PDs come in a huge variety. Focusing on solid-state PDs, the two main classes of operation are photoconductive and photovoltaic.[3,4] The latter includes photodiodes, which are by far the most common type. Considering applications, the relevant figures of merit are responsibility, detectivity, and bandwidth.[5–7] The functional section of a photodiode is the depletion region of the p–n junction or Schottky junction.[8–10] The built-in electric field separates the photogenerated minority electrons and holes to generate a photocurrent in short-circuit configuration, a photovoltage in open-circuit configuration and electrical power when a load resistance is connected.

We have previously introduced the InGaN/SiNx/Si uniband diode, which operates qualitatively different than conventional p–n diodes and Schottky diodes.[11] The diode is based on the alignment of the conduction band of InGaN with the valence band of Si for an In content around 40%. Therefore, the direct junction of n-InGaN and p-Si is ohmic due to majority electron–hole recombination at the interface for forward bias and majority electron–hole generation for reverse bias. Upon insertion of the SiNx thin insulating interlayer, the I–V characteristics changes to rectifying. The SiNx interlayer is formed by nitridation of the Si surface for 20 min prior to In0.4Ga0.6N growth by plasma-assisted molecular beam epitaxy (PA-MBE). At forward bias the current is governed by the transition from direct tunneling to Fowler–Nordheim tunneling of holes, followed by electron–hole recombination. At reverse bias, the current is blocked as the insulating SiNx interlayer hinders the electron–hole generation at the same location. At zero bias, all energy bands are flat. There are no depletion regions and built-in electric fields. Therefore, at first glance, a photoresponse such as in conventional photodiodes is not expected. However, considering pure diffusion of photogenerated minority electrons in the p-Si layer and photogenerated minority holes in the n-InGaN layer, still, one-half of the charge carriers diffuses towards the SiNx interlayer at the InGaN/SiNx/Si heterojunction. Upon passing the SiNx interlayer by tunneling, energy relaxation, and diffusion, the electrons and holes are separated and prevented from recombination at the interface. A photocurrent evolves. This establishes the InGaN/SiNx/Si uniband diode PD.

Here, we study the photocurrent properties of the InGaN/SiNx/Si uniband diode PD. First, we recall the I–V characteristics of the uniband diode in the dark. This allows to determine the discontinuities of the majority and minority carrier energy bands from the transition of hole direct tunneling to Fowler–Nordheim tunneling, as well as the effective SiNx interlayer thickness. Next, wavelength, power- and time-dependent measurements of the photocurrent are performed to deduce the responsivity, specific detectivity and bandwidth. Two distinct operation modes (i) for longer and (ii) for shorter incident light wavelengths are identified. Operation mode (i) involves absorption in Si and electron
direct tunneling through the SiN<sub>x</sub> interlayer followed by energy relaxation. Operation mode (ii) involves absorption in InGaN, energy relaxation of holes and transport across the SiN<sub>x</sub> interlayer. Finally, the noise performance is studied. The noise is much larger in operation mode (i) than in operation mode (ii). This is attributed to the presence of the tunnel barrier for electrons in operation mode (i) and sole hole relaxation without the presence of energy barriers in operation mode (ii). In view of dual-wavelength photodetection noise is introduced as an independent, convenient parameter to distinguish between longer and shorter wavelength regions.

2. Results and Discussion

Figure 1a shows the ω−2θ X-ray diffraction (XRD) spectrum recorded around the InGaN (0002) Bragg reflection. The InGaN (0002) reflection is centered at 16.67°, giving an In content of 40% by applying Bragg’s law and Vegard’s law.[12] The photoluminescence (PL) spectrum of the InGaN layer taken at room temperature is shown in Figure 1b. It exhibits the peak around 2.0 eV, providing a rough estimate of the bandgap energy. Figure 1c,d shows the top-view scanning electron microscopy (SEM) image and cross-sectional SEM image of the InGaN layer on the Si (111) substrate. The InGaN layer exhibits a dense, columnar structure, typical for the direct growth of In-rich InGaN on Si without any GaN or AlN buffer layers. Energy-dispersive X-ray spectroscopy (EDS) element mappings of In, Ga, N, and Si are shown in Figure S1, Supporting Information.

Figure 2a shows a scheme of the uniband diode PD. The I−V curve in the dark is shown in Figure 2b with linear current scale and in the inset with logarithmic current scale. The polarity refers to the Si back contact. The rectification ratio is 50 at ±4 V. The corresponding Fowler–Nordheim plot for forward bias is shown in Figure 2c. With increasing voltage, the transition from direct tunneling with ohmic, logarithmic dependence of \[ \ln(I/V^2) \] on \( 1/V \) to Fowler–Nordheim tunneling with negative linear dependence of \[ \ln(I/V^2) \] on \( 1/V \) is at 150 mV.[11−17] This lets us construct the complete band diagram, shown in Figure 2d: Starting point is the alignment of the n-InGaN conduction band with the p-Si valence band at zero bias. The 150 mV transition voltage then implies that the forward current is governed by majority hole tunneling through the SiN<sub>x</sub> interlayer from p-Si to n-InGaN, followed by electron–hole recombination. Therefore, the Si/SiN<sub>x</sub> valence band offset \( \Delta E_v \) is 150 meV.

Assuming the same ratio of the conduction band offset and valence band offset of SiN<sub>x</sub> and stoichiometric Si<sub>3</sub>N<sub>4</sub> with Si of 2.4 eV/1.8 eV,[18,19] the Si/SiN<sub>x</sub> conduction band offset \( \Delta E_c \) is 200 meV. The SiN<sub>x</sub> bandgap energy becomes 1.5 eV, adding the Si bandgap energy of 1.1 eV to the band offsets \( \Delta E_c \) and \( \Delta E_v \). This low bandgap energy of SiN<sub>x</sub> corresponds to a substoichiometric x-value of 0.4–0.5, taking the bandgap energy of Si<sub>3</sub>N<sub>4</sub> of 5.3 eV. In the literature, the x-value is barely given.[20] The bandgap energy of InGaN of 2.0 eV is taken from the PL measurement.

Last, the SiN<sub>x</sub> tunnel barrier thickness \( d \) is calculated. This requires the electron effective mass and hole effective mass of SiN<sub>x</sub>. When assuming that the electron- and hole effective
masses of SiN\textsubscript{x} linearly scale with the bandgap energy from Si to Si\textsubscript{3}N\textsubscript{4}, the electron effective mass of SiN\textsubscript{x} is 0.23 \( m_0 \). The hole effective mass of SiN\textsubscript{x} is 0.5 \( m_0 \). \( m_0 \) is the free electron mass. This uses the following parameters: Bandgap energy of Si: 1.1 eV; bandgap energy of Si\textsubscript{3}N\textsubscript{4}: 5.3 eV; effective electron mass of Si: 0.2 \( m_0 \); effective electron mass of Si\textsubscript{3}N\textsubscript{4}: 0.5 \( m_0 \); effective hole mass of Si: 0.5 \( m_0 \); effective hole mass of Si\textsubscript{3}N\textsubscript{4}: 0.23 \( m_0 \). Then, the SiN\textsubscript{x} tunnel barrier thickness \( d \) is determined from the transmission coefficient \( T_b \) for hole direct tunneling from p-Si to n-InGaN.\textsuperscript{[23]} 
\[
T_b \approx \exp \left( - \frac{\hbar d}{2 \sqrt{\frac{2 m_h}{\Delta_E}}} \right),
\]
where \( m_h \) is the hole effective mass of SiN\textsubscript{x} and \( \hbar \) is the reduced Planck constant.

\( T_b \), in turn, is determined from the hole direct tunnel resistance \( R_h \) and the series resistance \( R_s \). Close to zero forward bias, the total resistance is the sum of \( R_h \) and \( R_s \), amounting to \( R_h + R_s = 670 \Omega \) and the transmission coefficient is \( T_h \). \( R_s \) of 15 \( \Omega \) is determined from the \( I-V \) curve above 2 V forward bias where the Fowler–Nordheim tunnel resistance for the holes becomes negligible, corresponding to a transmission coefficient of 1. Therefore, \( T_h \) is roughly estimated by \( R_s/(R_h + R_s) = 0.02 \). This gives \( d = 1.3 \text{ nm} \). The value is somewhat smaller than the InGaN interlayer thickness seen in high-resolution transmission electron microscopy (TEM) of 2–3 nm.\textsuperscript{[24,25]} This can be expected due to the thickness and composition variations of the SiN\textsubscript{x} interlayer formed by the high-temperature Si nitridation process.

The band structure of the InGaN/SiN\textsubscript{x}/Si uniband diode PD resembles that obtained for certain combinations of 2D materials, which are also extensively studied for the realization of PDs. The essential difference for device functionality is the constant band offsets for the InGaN/SiN\textsubscript{x}/Si uniband diode PD with applied bias due to the covalent bonds at the interfaces. In contrast, the band offsets for 2D materials can freely adjust due to the van der Waals bonds at the interfaces.\textsuperscript{[15,26–29]}

Under illumination, the \( I-V \) curves with logarithmic current scale for the InGaN/SiN\textsubscript{x}/Si uniband diode PD are shown in Figure 3a for different wavelengths of the incident light: 808, 638, 532, and 405 nm and 10 mW cm\textsuperscript{-2} excitation power density. The \( I-V \) curves with reduced linear scales around zero are shown in the inset. The dark \( I-V \) curve is shown for comparison. For the discussion, we focus on the current at zero and reverse bias which is the common operation regime of photodiodes. The corresponding Fowler–Nordheim plots for reverse bias are shown in Figure 3b. The reverse current increases from 405 to 638 nm wavelengths of the incident light and drops for 808 nm wavelength of the incident light. In the Fowler–Nordheim plot, only direct tunneling or ohmic resistance are observed, as indicated by the logarithmic dependence of \( \ln(I)/V^2 \) on \( 1/V \). The wavelength dependence provides a first hint of the two distinctly different operation modes (i) and (ii) of the InGaN/SiN\textsubscript{x}/Si uniband diode PD, sketched by the energy band diagrams in Figure 3c,d, together with the transport of the photogenerated electrons and holes at zero bias.

In operation mode (i) for the longer wavelengths of 808 and 638 nm, the incident light is mainly absorbed in the Si substrate. Photogenerated minority electrons in p-Si diffuse towards the SiN\textsubscript{x} interlayer, pass the SiN\textsubscript{x} interlayer by direct tunneling and relax in energy to the InGaN conduction band. The photogenerated holes diffuse in the opposite direction. In operation...
In operation mode (ii) for the shorter wavelengths of 532 and 405 nm, the incident light is mainly absorbed in the InGaN layer. Photogenerated minority holes in n-InGaN diffuse toward the SiN interlayer, relax in energy to the SiN valence band, pass the SiN interlayer by diffusive transport and relax in energy to the Si valence band. The photogenerated electrons diffuse in the opposite direction. The incident light with the wavelength of 638 nm with energy very close to the bandgap energy of InGaN falls out of this scheme. Absorption is distributed over the InGaN layer and the Si substrate.

The increase of the photocurrent for 405–638 nm wavelengths of the incident light is explained by the increasing absorption length, such that more photogenerated minority holes in n-InGaN diffuse toward the SiN interlayer before recombination with majority electrons. Trivially, the number of photons is larger for longer wavelengths for the same excitation power density. The drop of the photocurrent for 808 nm wavelength of the incident light is mainly absorbed in the InGaN layer. Photogenerated carrier transport for longer and shorter wavelengths of incident light. The excitation power density for different wavelengths of incident light. The wavelengths of incident light are 808, 638, 532 and 405 nm. The nitridation times for the samples are 1, 5 and 20 min, labeled as M1, M2 and M3.

Regarding reverse bias operation, the dark current is quite high. In operation mode (ii), the series resistance dominates. The dark current can be suppressed by reducing the transmission coefficient for the direct tunneling of majority holes for wider SiN tunnel barrier thickness, assuming the band offsets and barrier thickness is unchanged. This, however, also suppresses the electron tunneling and photocurrent in operation mode (i). The balance of the dark current and photocurrent as a function of the SiN tunnel barrier thickness is reflected in the ratio of the hole- and electron direct tunnel transmission coefficients, $T_h/T_e = \exp(-2(dk-k'))$. $T_h$ and $T_e$ are calculated from $T_{h/e} = \exp\left(-2d\sqrt{\frac{2m_{h/e}}{\hbar^2}}\Delta E_{h/e}\right)$. $k$ and $k'$ are the attenuation coefficients for holes and electrons, respectively, with dimension of inverse length and $d$ is again the SiN tunnel barrier thickness. The electron direct tunnel resistance $R_e = 148 \, \Omega$ for the present InGaN/SiN/Si uniband diode PD. Hence, the InGaN/SiN/Si uniband diode PD is best suited for operation at zero bias where the dark current is zero and only the thermal noise current remains.
Figure 4a–d shows the photocurrents and dark currents at zero bias under chopped illumination for varying excitation power density for the four wavelengths of the incident light: 808, 638, 532, and 405 nm. Transients of the photocurrent with higher time resolution are shown in Figure 4e,f for 808 and 532 nm wavelengths of the incident light with 50 mW cm$^{-2}$ excitation power density. The rise times and fall times $\tau_{\text{rise}}$ and $\tau_{\text{fall}}$ are defined as the time intervals for rising to 90% of the steady state photocurrent or for falling to 10% of the steady state photocurrent and are indicated in the figure. For 808 and 532 nm wavelengths of the incident light, the rise times are 57.1 and 137 $\mu$s and the fall times are 92.7 and 135 $\mu$s. The 3 dB bandwidth $B_{3\text{dB}}$ is determined from the rise time, $B_{3\text{dB}} = 0.35/\tau_{\text{rise}}$. From these data, the photocurrent, responsivity $R = I_{\text{ph}}/P$ and specific detectivity $D^* = \frac{R}{\sqrt{A P}}$ as a function of the excitation power density for the four wavelengths of the incident light are derived, as shown in Figure 4g–i. $I_{\text{ph}}$ is the photocurrent, $P$ is the excitation power, $I_{\text{n}}$ is the measured thermal noise current in the dark at zero bias of $8 \times 10^{-10}$ A, and $A$ is the detector area of 0.14 cm$^2$.

The photocurrent increases with excitation power density, following a power law $I_{\text{ph}} \approx P^\theta$. The photocurrents for 50 mW cm$^{-2}$ excitation power density are 0.48 mA for 808 nm light, 0.91 mA for 638 nm light, 0.26 mA for 532 nm light, and 0.048 mA for 405 nm light. $\theta$ is 0.81, 0.85, 0.80, and 0.94 for 808, 638, 532 and 405 nm. $\theta$ is related to trapping and recombination processes of photogenerated carriers \cite{30–32}. There is no obvious trend, indicating that these processes are not significant, neither in Si nor InGaN. The responsivity and specific detectivity reveal the same dependence on the wavelengths of the incident light as the photocurrent due to excitation either in Si or InGaN. The specific detectivity is governed by the responsivity rather than by the noise. The maximum responsivity is 160 mA W$^{-1}$ and the maximum specific detectivity is $4.8 \times 10^8$ Jones for 638 nm light and 10 mW cm$^{-2}$ excitation power density. The slight decrease of $R$ and $D^*$ with excitation power density might be due to heating.

The faster response for longer wavelength, 808 nm, compared with the response at shorter wavelength, 532 nm, is further consequence of the two different operation modes. In general, the response time is determined by the slowest process in the PD, which is the hole diffusion for the InGaN/Si$_x$/Si uniband diode PD. The faster response at 808 nm for absorption in Si compared with the response at 532 nm for absorption in InGaN is,
The sole relaxation of holes and transport across the SiN/Schottky junctions and single tunnel junctions.\cite{36,37}

– by the directional, uncorrelated transport in p-trons due to the discreteness of the elementary charge and is generated and thermal noise extending to the highest frequencies. Shot noise and thermal noise exhibit white noise spectra with constant spectral power as a function of frequency while 1/f noise increases for low frequencies.\cite{33} 1/f noise is associated with contacts, surfaces and other potential barriers.\cite{34,35} Thermal noise depends on temperature and ohmic resistances of the circuit. Shot noise arises due to the discreteness of the elementary charge and is generated by the directional, uncorrelated transport in p-n junctions, Schottky junctions and single tunnel junctions.\cite{36,37}

**Figure 5a** shows the time dependence of the photocurrent at zero bias for the wavelengths of the incident light of 808 and 532 nm. The excitation power density is adjusted such that the average photocurrents are the same. Plots for larger photocurrents are shown in Figure S3, Supporting Information. The photocurrent noise for operation mode (i) with 808 nm incident light wavelength is about four times larger than that for operation mode (ii) with 532 nm incident light wavelength. To make sure the noise characteristics is intrinsic for the InGaN/SiN\textsubscript{x}/Si uniband diode PD, a commercial Si photodiode is used for comparison. For the longer wavelength, the Si photodiode the noise does not depend on the incident light wavelength, as shown in Figure S4, Supporting Information. The photocurrent spectral power is shown in Figure 5b, Supporting Information. Over the whole assessed frequency range, the spectral power of the noise is larger for operation mode (i) than for operation mode (ii).

This can be well explained by the direct tunneling of electrons through the SiN\textsubscript{x} interlayer in operation mode (i) and the sole relaxation of holes and transport across the SiN\textsubscript{x} interlayer in operation mode (ii). Clearly, the total PD noise in Figure 5a is dominated by 1/f noise and provides a novel measure for dual-wavelength photodetection.

**3. Conclusion**

In conclusion, the photocurrent properties of an InGaN/SiN\textsubscript{x}/Si uniband diode PD have been investigated in detail. The full band structure has been first constructed from the transition of direct tunneling to Fowler–Nordheim tunneling of holes at forward bias in the dark. Starting point is the alignment of the n-InGaN conduction band with the p-Si valence band at zero bias.

In photocurrent measurements of the responsivity, detectivity, and bandwidth, two distinct operation modes have been indicated. At longer wavelengths of the incident light, absorption in Si is followed by electron direct tunneling and energy relaxation. At shorter wavelengths of the incident light, absorption in InGaN is followed by hole energy relaxation and diffusive transport across the SiN\textsubscript{x} interlayer. The photocurrent noise was found to be much larger at longer wavelengths than at shorter wavelengths. For dual-wavelength photodetection noise has been introduced as versatile parameter for wavelength discrimination.

**4. Experimental Section**

**Materials Growth:** The In\textsubscript{0.4}Ga\textsubscript{0.6}N layers were grown by PA-MBE on p-type Si (111) substrates. Prior to growth, the Si substrates were etched in 10% HF solution for 1 min to remove the native oxide from the surface. The cleaned substrates were transferred into the load chamber and degassed for 30 min at 300 °C. Then, the substrates were transferred into the growth chamber and annealed at 900 °C (thermocouple reading) to remove residual native oxide. The thin SiN\textsubscript{x} layer was formed at the same temperature by exposure to active N flux with radio-frequency plasma source power of 350 W and 1.7 standard cubic centimeters per minute (sccm) \textit{N}_2 flow for 20 min. For the growth of InGaN, the substrate temperature was reduced to 620 °C and the N plasma source settings were 220 W and 1.2 sccm. The In and Ga effusion cell temperatures were 814 °C and 845 °C with the In and Ga beam equivalent pressures of 1.05 × 10\textsuperscript{-9} Torr and 7.47 × 10\textsuperscript{-8} Torr, respectively. The growth time was 1 h without growth interruptions.

**PD Fabrication and Active Area:** The InGaN/SiN\textsubscript{x}/Si uniband diode PDs were fabricated by deposition of Ga–In eutectic droplets on the InGaN layers and the backside of the Si substrates. The ohmic behavior of the contacts is shown in Figure S5, Supporting Information. The illuminated area is given by the total surface area minus the contact area. For the investigated small sample of triangular shape with 0.2 cm base length and a single contact in the center, see Figure S6, Supporting Information, the illuminated area equals the active area. This is concluded from the photocurrent, which is smaller than that for a large sample measured for comparison. For the large sample, not all illuminated area contributes to the photocurrent. The current collection area around the contact is smaller. Therefore, the smaller photocurrent for the small sample implies that the total surface area is less than the current collection area around the contact. The whole surface area is active. The active area is 0.14 cm\textsuperscript{2}.
Materials and PD Characterization: The In content of the InGaN layers was determined by XRD (Bruker D8). The morphology and cross-section of the InGaN layers were assessed by field-emission scanning electron microscopy (SEM, Zeiss Gemini 500). Element EDS element mappings were performed with the EDS spectrometer (Aztec X-Max 80) attached to the SEM. PL spectra were taken at room temperature with the 100 mW, 532 nm line of a Nd-YAG solid-state laser as excitation source and a silicon CCD attached to a single monochromator for detection. The I–V curves were measured using a Source Meter (Keithley-2400). The response time was measured using a chopper and a current amplifier (SR570). A fast Fourier transform (FFT) signal analyzer and a current amplifier and a current amplifier were used to record the photocurrent noise. Four diode lasers with wavelengths of 808, 638, 532, and 405 nm were used as light sources. All measurements were carried out at room temperature under ambient conditions.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords
Fowler–Nordheim tunneling, InGaN, photodetectors, silicon nitride, sub-Poissonian shot noise, unibond diodes

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