Frequency response and bandwidth enhancement in Ge/Si avalanche photodiodes with over 840GHz gain-bandwidth-product

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Abstract: In this work we report a separate-absorption-charge-multiplication Ge/Si avalanche photodiode with an enhanced gain-bandwidth-product of 845GHz at a wavelength of 1310nm. The corresponding gain value is 65 and the electrical bandwidth is 13GHz at an optical input power of −30dBm. The unconventional high gain-bandwidth-product is investigated using device physical simulation and optical pulse response measurement. The analysis of the electric field distribution, electron and hole concentration and drift velocities in the device shows that the enhanced gain-bandwidth-product at high bias voltages is due to a decrease of the transit time and avalanche build-up time limitation at high fields.

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References and links


1. Introduction

A wide range of applications require photodetectors with high sensitivity to detect weak optical signals. In addition to high data rate communication applications, new areas in imaging, biotechnologies, sensing and quantum cryptography also have a need for such photodetectors.

High sensitivities can be achieved by using avalanche photodetectors (APDs), which use internal gain to reduce the noise of the first stage electrical amplifier. The APDs can be
characterized through two functions that can be optimized separately. The first function is the absorption of light and its conversion to an electrical signal. The second function is the amplification of this electrical signal through the avalanche process. However, the avalanche multiplication process that generates the internal gain, limits the speed performance of the APD due to the avalanche buildup time, which is related to the ratio of the electron and hole ionization coefficients [1]. Due to the large asymmetry of electron and hole ionization coefficients in silicon (Si), this material is very attractive for APDs [2]. However, Si is not appropriate to absorb at the telecommunication wavelengths, which require the use of smaller bandgap materials such as germanium (Ge).

As a result, APDs with a Ge absorption layer and a Si multiplication layer can achieve very good performance with high quantum efficiency and low noise [3]. In addition, the multiplication gain and frequency response represent very important figures of merit to determine the performance of APDs. The product of these is the gain-bandwidth-product (GBP), which is usually constant at high gains [1]. Although the 4% lattice mismatch between Ge and Si can result in a high dark current, careful processing and the right annealing temperature can reduce the impact of threading dislocations.

Monolithically grown Separate-Absorption-Charge-Multiplication (SACM) Complementary Metal-Oxide-Semiconductor (CMOS) compatible Ge/Si APDs have recently demonstrated 340GHz GBP. This is higher than standard III-V APDs that exhibit limited GBPs around 120GHz [3]. The same device exhibits dramatically enhanced GBPs at elevated bias voltage and a GBP value of 845GHz is reported here from a 30µm-diameter device.

Similar unconventional behavior in GBPs at high voltages have been observed by G. Kim et al. in InGaAs/InAlAs APDs [4], H.S. Kang et al. in Si APDs [5] and J.W. Shi et al. in Si/SiGe APDs [6]. We use detailed analysis of carrier transport to explain the effects observed in our devices and associate the frequency response enhancement primarily to the decrease of the transit time and multiplication time limitation due to space charge effects. The following pulse response results support this explanation. The measured GBP makes such SACM Ge/Si APDs attractive for data rates of 40Gbit/s and above.

2. Measured and simulated device structures

Figures 1(a) and 1(b) illustrate the real device structure with the corresponding layer properties. The device consists of an intrinsic Si multiplication layer and an intrinsic Ge absorption layer, separated by a p-doped Si charge layer, which controls the electric field distribution in the device [3]. The structure was simulated using ATLAS assuming a uniform doping profile without any surface and interface defects or Ge/Si interdiffusion (Fig. 1(c)).
3. Experimental and simulation results

The measured and simulated IV curves are illustrated in Fig. 2. The total current in Fig. 2(a) is measured on a 30μm-diameter APD under an optical input power of −20dBm at 1310nm using a Fabry-Perot laser as the light source. The same parameters are used in the simulation, which shows similar IV characteristics in Fig. 2(b). The breakdown voltage, defined as the voltage for a dark current of 10μA, is measured to be −24V, whereas the simulated value is −26.4V. It can also be seen that the simulated breakdown is more abrupt than in the measurements due to the two-dimensional ideal structure.

The measured gain is determined by normalizing the responsivity of the APD to the primary responsivity of a p-i-n device fabricated on the same wafer. The primary responsivity is 0.55A/W at 1310nm and the correspondent external quantum efficiency is 52.2%. The simulated gain can be determined through dividing the calculated photocurrent, i.e., the difference between total current and dark current, by the available photocurrent in the device. The available photocurrent is defined as the current generated from the photoabsorption in the structure, which takes into account the light reflection at the device surface and layer interfaces, absorption coefficient and absorption layer thickness.

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Fig. 1. (a) Schematic drawing and (b) a scanning electron microscope (SEM) cross sectional image of the Ge/Si SACM APD device. (c) Schematic layer view of the simulated structure.

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Fig. 2. (a) Measured and (b) simulated dark current and total current on a 30μm-diameter Ge/Si SACM APD versus bias voltage under an optical power of −20dBm at 1310nm.
The direct current (DC) gain from injected electrons can be theoretically given from [1] as

\[ M_n = \left( \frac{\alpha - \beta}{\alpha - \beta} \right) e^{d \left( \frac{\alpha - \beta}{\alpha - \beta} \right)}, \]  

(1)

where \( d \) is the multiplication region width and \( \alpha \) and \( \beta \) are the electron and hole ionization coefficients, respectively, which depend strongly on the electric field. These coefficients can be approximated by the following expressions [7]

\[ \alpha = A_n e^{-\frac{A_n}{E}} \quad \text{and} \quad \beta = A_p e^{-\frac{A_p}{E}}, \]  

(2)

where \( E \) is the electric field and \( A_n, A_p, B_n, B_p \) are material dependent parameters, which can be determined experimentally. Consequently, the gain increases exponentially with the electric field and hence with the bias voltage.

Figure 3 shows the measured as well as the simulated gain curves at different optical powers. The gain simulation is based on Selberherr’s impact ionization model in Si with \( A_n = 7.03 \times 10^5 \text{cm}^{-1}, A_p = 1.58 \times 10^5 \text{cm}^{-1}, B_n = 1.231 \times 10^6 \text{cm}^{-1} \) and \( B_p = 2.036 \times 10^5 \text{cm}^{-1} \) for \( E < 4 \times 10^5 \text{Vcm}^{-1} \), \( A_n = 7.03 \times 10^5 \text{cm}^{-1}, A_p = 6.71 \times 10^5 \text{cm}^{-1}, B_n = 1.231 \times 10^6 \text{cm}^{-1} \) and \( B_p = 1.693 \times 10^6 \text{cm}^{-1} \) for \( E \geq 4 \times 10^5 \text{Vcm}^{-1} \) [8]. Both measurement and simulation results show akin behavior with an exponential gain increase until a certain bias voltage. As the bias voltage increases more, the gain decreases though, exhibiting a similar result reported by H.S. Kang et al. and J.W. Shi et al. [4,5]. The gain reduction indicates that the electric field is reduced in the multiplication region.

Figure 3 shows also that the optical input power has a big impact on the multiplication gain. The gain is reduced at higher optical powers due to a change of the electric field distribution in the multiplication region because of a change in the free carrier densities. The highest achieved gain on a 30\( \mu \)m-diameter device is 90 at \(-30\text{dBm}\) and 33 at \(-20\text{dBm}\). Two differences are present between simulation and measurement. The simulated gain in Fig. 3(b) attains higher values, around two times higher than measured values, and then decreases very fast, resulting in a sharp peak. This is due to the ideal structure, which has \textit{inter alia} large electrodes in comparison to the real device. In addition the real structure exhibits higher dark current, which originates mainly from dislocations and tunneling at the Ge/Si interface [3]. These effects are not included in the simulated structure.

![Fig. 3. (a) Measured and (b) simulated gain curves versus bias voltage under \(-20\text{dBm}, -26\text{dBm}\) and \(-30\text{dBm}\) at 1310nm.](image-url)
To characterize the frequency response of the APD, a lightwave component analyzer with an internal laser and optical modulator operating at 1310nm is used. The set of the frequency response curves depicted in Fig. 4(a) are measured under ~20dBm input power at bias voltage values between ~24V and ~28V. We can clearly see that the response at low frequencies follows a similar behavior as the DC-gain curve from Fig. 3(a). However, the response at high frequencies keeps increasing. Consequently, the origin of the reported electrical 3dB-bandwidth (BW) enhancement, which is illustrated in Fig. 5(a), is not only due to the enhancement at high frequencies, but also due to the decrease of the response at low frequencies.

Figure 4(b) shows the simulated frequency response. It can be clearly seen from the figure that the low frequency response increases by increasing the bias voltage until ~26.5V and then decreases again, whereas the high frequency part above around 9GHz keeps increasing. This behavior agrees well with the measurements. The insets of Fig. 4 represent the normalized frequency response. The observed peaking in the insets, noted as radio-frequency (RF) resonance or RF-peaking [5,6], in both experiment and simulation is due to two-dimensional effects and contributes fractionally and not principally in the BW enhancement. More simplified simulated structures that have stacked layers with the same area dimensions and electrodes arranged oppositely to each other exhibit also BW enhancement without the existence of any peaking in the frequency response.

Figure 5 shows the voltage dependence of the BW. It can be seen that the BW decreases between ~23V and ~26V and then increases again due to the frequency response enhancement, exceeding 10GHz. At around ~23V, the APD is RC and transit time limited, since the multiplication gain is low. As the voltage increases to ~26V and the gain reaches its maximum, the avalanche buildup time, also called multiplication time, increases and hence the BW drops. As the voltage increases above ~26V, the gain drops and thus the multiplication time, giving a raise to the BW. However, the BW in this enhanced mode is higher than the transit time limited BW at lower voltages. This is explained below by investigating the internal properties such as the electron and hole drift velocities across the Ge absorption layer.

Figure 5 shows also the impact of optical power on the BW. Around ~23V, there is no considerable influence, and the BW value is almost constant. As the bias voltage increases, any perturbation of the electric field through excess of charge carriers has a big influence on the gain and on the speed performance of the APD. This behavior is in general due to the trade-off between the gain and the BW. High optical powers produce low gains and high BWs, and vice versa.
Figure 5. (a) Measured and (b) simulated electrical 3 dB-BW versus bias voltage under 
$-20$ dBm, $-26$ dBm and $-30$ dBm at 1310nm.

Figure 6(a) shows the extracted GBP of the APD under different input powers. The GBP is proportional to the gain increase at low gain values due to the constant BW. As the gain increases, the BW drops due to the multiplication time, and the GBP saturates [1]. Beyond the gain peak, the GBP starts to increase again dramatically because of the BW enhancement and the slow decrease of the gain. The highest measured GBP is 845GHz at $-30$ dBm, corresponding to a gain of 65 and a BW of 13GHz. The simulated GBP in Fig. 6(b) exhibits some differences to the measurement results. One difference appears in the lower GBP values in the simulation, especially after the gain peak. This is expected since the simulated gain falls off much faster than is measured.

To investigate the very high GBP of the Ge/Si APDs, a pulse response measurement is realized using a Digital Communication Analyzer with 28GHz optical BW and a 1.55µm femtosecond fiber-laser with 20MHz repetition rate and 600fs pulse-width. Figure 7 depicts the pulse responses taken at $-20$V to $-30$V under average optical input powers of $-20$dBm and $-26$dBm.

The pulse response exhibits a similar behavior to the frequency response, where a slow, low frequency part increases with increased bias voltage until around $-26$V and then decreases, whereas a fast, high frequency part continues to increase. We believe that the slow pulse part results from low carrier drift velocities in the absorption region, as described below. It can be seen that the pulse width becomes very narrow at higher bias voltages than $-26$V, which means that the APD becomes faster. The full width at half maximum (FWHF) at $-30$V
is 37ps at −20dBm and 30ps at −26dBm, which is in agreement with the enhanced GBP behavior that rises at lower optical powers.

![Fig. 7. Measured pulse responses at different bias voltages under an optical power of (a) −20dBm and (b) −26dBm at 1550nm.](image)

At high bias voltages, the space charge effect from the large amplified photo and dark currents cannot be ignored [9], and we can understand the trends by examining the spatial dependence of the electric field. The behavior of the electric field in the multiplication layer illustrated in Fig. 8 explains clearly the decrease of the gain after −26.5V. Since the gain depends exponentially on the ionization coefficients, which depend exponentially on the electric field, any small change in the electric field influences strongly the gain behavior.

The zoom-in in Fig. 8 indicates an increase of the electric field in the middle of the multiplication layer as the bias voltage is increased to −26.5V and then a drop at higher values, which agrees well with the DC gain measurements. The electric field part at the edge between the charge layer and the multiplication layer increases, however, continuously and therefore can be the reason for the high frequency gain, which was also observed to increase continuously. The electric field in the absorption region is relatively small, resulting in low electron and hole velocities, which result in the relatively slow tail in the impulse response. Since the voltage across the device is constant, the reduction of the field in the multiplication region at voltages above −26.5V causes the field in the absorber to rise, reducing the electron and hole transit times, resulting in shorter impulse responses.

![Fig. 8. Simulated electric field distribution in the APD at different bias voltages. The inset shows the zoom-in electric field in the Si multiplication layer.](image)

Figure 9 illustrates both simulated hole and electron concentration profiles at different biases. At high bias voltages when the density of electrons and holes become comparable to
the density of donors in the multiplication region ($\approx 5 \times 10^{15}$ cm$^{-3}$), the electric field profile can be affected through the space charge of these electrons and holes. Because of the net excess in holes at the edge between the charge and the multiplication region, the magnitude of the electric field increases there. The net excess in electrons in the multiplication region and at the edge to the n$^+$-contact layer causes the decrease of the electric field magnitude, and therefore of the multiplication gain due to the exponential dependence of the gain on the electric field [9].

![Fig. 9. Simulated electron and hole concentration in the APD at different bias voltages.](image)

To understand in detail the BW enhancement in SACM Ge/Si APDs, the electron and hole drift velocities are now studied and are illustrated in Fig. 10. It can be seen that the electron and hole velocities have reached their saturation values in the Si multiplication layer even at low bias voltages through the high electric field in that region, whereas in the Ge layer the drift velocities reach the saturation values only at around $-26.5\,\text{V}$. At lower voltages, the velocities are very small in Ge due to the low electric field, so that the transit time is relatively high and reaches its minimum only at voltages higher than $-26.5\,\text{V}$, where the drift velocities reach their maximum. This explains well the BW enhancement above $-26.5\,\text{V}$, which uses the fact of the decrease of both multiplication and transit times.

![Fig. 10. Simulated electron and hole drift velocity in the APD at different bias voltages.](image)

The increase in GBP at higher voltages can be explained by the rise of hole velocity in the absorber layer and space charge effects. The experimental observation of shorter impulse response at higher voltages strongly supports this explanation. One should note in addition that the band discontinuities at the Ge/Si interface of the APDs have no impact on the GBP behavior at high bias voltages, since the discontinuities get flatten out through the high electric field in the device and smoothed out by the Ge/Si interdiffusion.
4. Conclusion

We have experimentally and theoretically investigated the frequency response enhancement in Ge/Si SACM APDs and demonstrated a GBP of 845GHz on a 30µm-diameter device. Both measurement and simulation show similarities in gain and BW behaviors. The enhancement behavior appears to be the result of decrease of the multiplication time limitation due to the gain drop through the space charge effect, and to reduction of the transit time because of the electric field increase in the Ge layer at high bias voltages.

Since the enhanced GBP depends strongly on the incoming optical power, the studied device, when operated in enhanced mode, has more advantages in some specific applications where the optical power is fixed, such as quantum cryptography. Future structures with smaller multiplication and absorption regions can exhibit GBPs over 400GHz in the normal mode, and perhaps over 1THz in the enhanced mode, especially at optical input powers lower than −30dBm.

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