Modelling Ge/Si Avalanche Photodiodes

F. Gity, J. M. Hayes, B. Corbett
Photonics Center, Tyndall National Institute
Lee Maltings, Prospect Row
Cork, Ireland
Farzan.Gity@Tyndall.ie

A. P. Morrison
Department of Electrical and Electronic Engineering
University College Cork
Cork, Ireland
a.morrison@ucc.ie

Abstract—**Ge/Si separate absorption, charge and multiplication avalanche photodiodes are investigated. The influence of the absorption thickness and doping, along with the charge and multiplication layer doping on the gain-profile, the breakdown voltage and the gain-bandwidth product are determined.**

Keywords-avalanche photodiode; gain-bandwidth product; germanium; optoelectronic devices; structural parameters

I. INTRODUCTION

Long wavelength Avalanche Photodiodes (APDs) are required for telecommunication optical integrated circuits due to their higher sensitivity and internal gain compared to PIN photodiodes. On the other hand, the avalanche multiplication process causes an internal noise related to the ratio of the electron and hole ionization coefficients [1] which limits the performance of the device. Si has a large asymmetry of electron and hole ionization coefficients, which makes it a useful candidate for APDs. However, Si is not able to absorb light at telecommunication wavelengths, unlike smaller band-gap materials such as Ge and InGaAs. InGaAs APDs have high multiplication noise that limits the gain-bandwidth product (GBP). APDs using Ge for absorption and Si for charge multiplication are more promising candidates having shown higher GBP [2]. Currently there are two approaches to fabricate Ge/Si APDs, Ge epitaxy on Si [2] and Ge/Si wafer bonding [3]. In this paper, a generalized structure is modelled to help decide the most appropriate fabrication approach and design of structural parameters depending on the APD requirements.

II. APD STRUCTURE

A schematic of the generalized Ge/Si separate absorption, charge and multiplication avalanche photodiode (SACM-APD) structure is shown in Fig. 1. The structure consists of a Ge absorption layer and a Si multiplication layer, separated by a p-doped Si charge layer, which is used to control the electric field distribution in the device. An additional Si layer is introduced between the charge layer and the physical interface in the Ge/Si SACM-APD structure. This layer separates the charge layer from the interface between the materials which may attract extra charge and therefore reduce control of the electric field in the multiplication region. The example device is cylindrical with a diameter of 30 μm and is simulated using the Silvaco TCAD simulation tool [4] under illumination of -30 dBm at 1.33 μm.

The static APD electric field for two different bias points is shown in Fig. 1. For bias voltages below breakdown voltage (red curve) the electric field in the multiplication region is below the critical value ($E_c \approx 4\times10^5$ V.cm^{-1} [4]) for Si for initialization of impact ionization. By increasing the bias voltage above breakdown (blue curve), the electric field distribution over the device is increased particularly in both the multiplication and the absorption regions. As a consequence, impact ionization and avalanching can take place. Higher electric field in the absorption layer will cause the minority carriers to travel toward the electrodes with higher velocity thereby increasing the bandwidth of the detector.

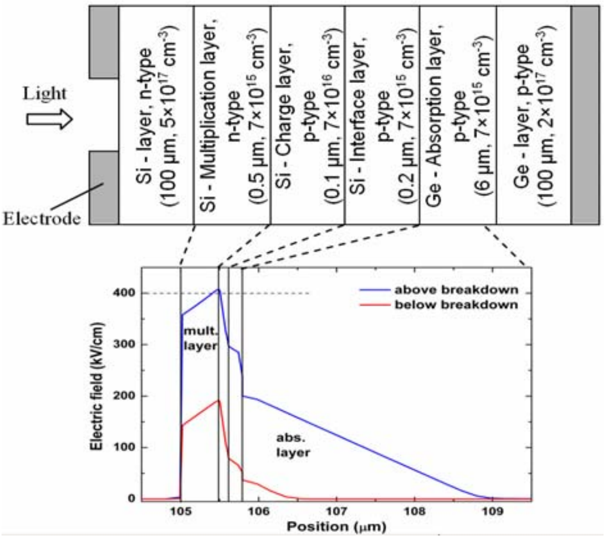

Fig. 1. Schematic of the Ge/Si SACM-APD base structure used in this work along with the static electric field distribution across the selected regions for two bias voltages.

III. SIMULATION RESULTS AND DISCUSSIONS

A. *Gain Profile and Breakdown Voltage*

Fig. 2 shows the dependence of the gain on voltage and on the thickness of the low doped Ge absorption layer. For absorption layer thicknesses less than 6 μm, the breakdown voltage varies significantly (inset Fig. 2), consequently the bias voltage referenced to the breakdown voltage (V_{bd}) of each structure is used (V_{bias} - V_{bd}) to allow fair comparison between devices. As shown in Fig. 2, by changing the absorption layer thickness, the peak gain and the full width at half maximum (FWHM) of the gain profile change. By increasing the thickness of the Ge absorption layer the voltage drop over this region is also increased, thereby increasing the absolute value of V_{bd} ($|V_{bd}|$). Hence, by designing the absorption layer thickness, the device will show a flat and a more stable gain-voltage profile.

This work is sponsored by Science Foundation Ireland (SFI) under grant 07/SRC/I1173.

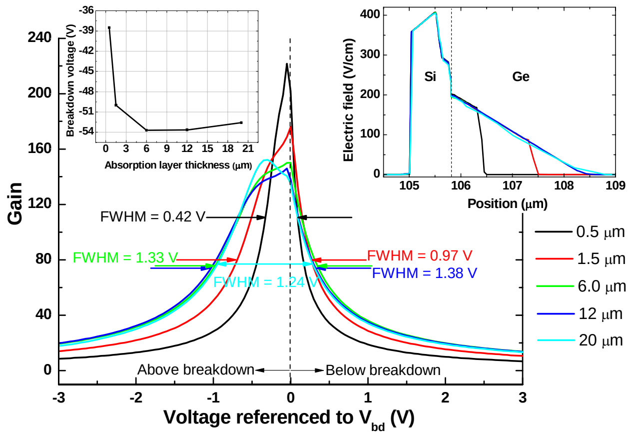

Fig. 2. Dependence of the Ge/Si APD gain on the absorption layer thickness. The insets show breakdown voltage and electric field dependence.

Fig. 3 shows the variation of the APD gain with the doping concentration in a 6 μm thick absorption layer. For any particular bias voltage a higher-doped absorption layer results in a smaller depletion penetration into this layer. As a result the greatest fraction of the electric field will be inside the multiplication layer. Therefore, the peak of the gain increases and the $|V_{bd}|$ decreases (inset of Fig. 3). Because the electric field is concentrated over the multiplication region, any small voltage drop due to high current flow near the breakdown voltage will cause the electric field inside this layer to drop below the critical value for impact ionization. The electric field reduction in the multiplication region results in a reduction in the gain which in turn will cause the gain-voltage profile to be very narrow. For the case of a lower-doped absorption layer, a portion of the electric field will be distributed across the absorption layer and hence the electric field drop near breakdown will be divided between the absorption and the multiplication layers, thus it will not decrease suddenly in the multiplication region. It is clear that reducing the doping level of the absorption layer, reduces the dependence of the gain on bias voltage.

B. Gain-Bandwidth Product (GBP)

Figs. 4 (a) and (b) show the voltage dependence of the GBP versus doping concentration in the multiplication and charge regions, respectively. By increasing the doping level in the multiplication layer the electric field distribution in some parts of this layer decreases dramatically (as indicated in the inset). As a result the gain reduces significantly which in turn reduces the avalanche build up time leading to an increase of the bandwidth [5]. However this increase in bandwidth is not enough to prevent the GBP from decreasing.

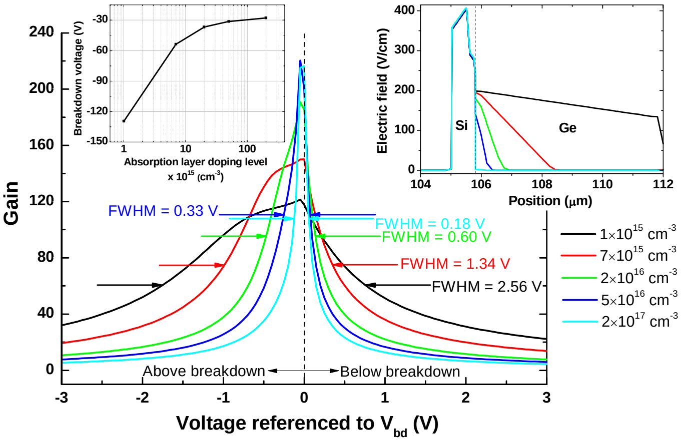

Fig. 3. Ge/Si APD gain-voltage profile for different absorption layer doping concentrations. The insets show breakdown voltage and electric field dependence.

As illustrated in Fig. 4 (b), by increasing the charge layer doping concentration the depletion region is kept inside the multiplication layer and the electric field increases (inset of Fig. 4 (b)). The GBP continues to increase after breakdown up to a point because the decreasing gain causes the bandwidth to increase and compensate the GBP.

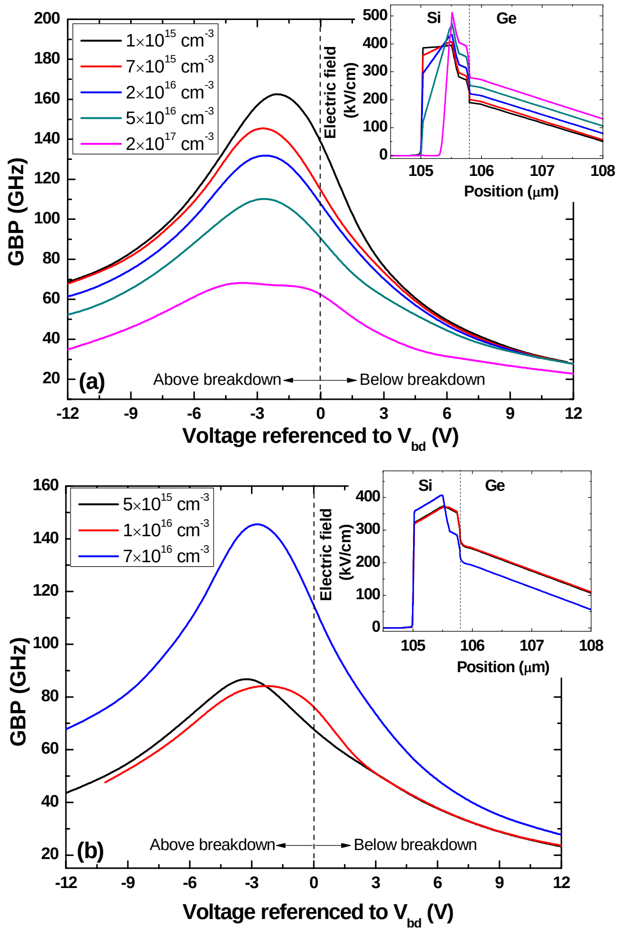

Fig. 4. GBP for different (a) multiplication layer and (b) charge layer doping concentrations. The insets show the electric field profiles for each structure.

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