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Design and Simulation of a Light-Activated Darlington Transistor Based on a SiCGe/3C-SiC Hetero-Structure*

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Abstract: A light-activated Darlington heterojunction transistor based on a SiCGe/3C-SiC hetero-structure is proposed for anti-EMI (electromagnetic interference) applications. The performance of the novel power switch is simulated using ISE. In comparison with the switches based on other polytypes of SiC, the design benefits from having fewer lattice mismatches between the SiCGe and 3C-SiC. A maximum common emitter current gain of about 890 and superb light-activation characteristics may be achievable. The performance simulation demonstrates that the device has a good I-V characteristic with a turn-on voltage knee of about 4V.

Key words: SiCGe; SiC; hetero-junction; Darlington transistor
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1　Introduction

Conventional electronic control systems are susceptible to electromagnetic interference (EMI) that can reduce the clarity of control signals. Light control systems that use optical signals to actuate the controlled interfaces have been suggested as a solution to the EMI problem. In order to develop an anti-EMI power switch for high temperature, high frequency, and high power applications, we proposed a light-activated SiC Darlington transistor in an earlier work[1]. Because SiC is not optically active in the wavelength range in which light sources are readily available for present optical communication, the ternary alloy SiCGe with appropriate composition was suggested as a light-absorption medium for the base layer to achieve its direct light-activation. However, that design is difficult to realize in practice because a second hetero-epitaxial growth of SiC emitter on SiCGe is necessary.

In comparison with SiGe/Si and SiCGe/Si heterojunctions, the SiCGe/SiC heterojunction structure has been less studied up to now, although a group from the University of Delaware has published an application of Si-C-Ge alloy in SiC hetero-structure bipolar transistors (HBT)[2]. This seems to be the only work currently on the Si-C-Ge ternary alloys used for fabrication of SiC HBT. However, the Ge content in their Si-C-Ge ternary alloy is only a few percent, which may not be enough to reduce the band-gap to meet the need of applications in the visible and infrared range. However, the feasibility of growing SiCGe alloys with higher Ge content on SiC substrates has been initially confirmed by our recent work[3].

We present here a new design of a SiC light-activated Darlington power transistor for which only one hetero-epitaxy is needed to make a monolithically integrated SiCGe/SiC heterojunction photodiode for providing a primary base current to the Darlington transistor. Also, the host material is changed to 3C-SiC in this new proposal because of two considerations. First, among SiC polytypes, 3C-SiC has the least lattice mismatch with the ternary alloy SiCGe; Second, 3C-SiC substrates are becoming more readily available[4].

SiCGe grown on 3C-SiC substrate is considered to have a cubic systematic lattice. According to Vegard's law, the lattice mismatch between

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$SiC_{1-x}Ge_x$ and 3C-SiC is only about one third of that between $SiC_{1-x}Ge_x$ and 4H- or 6H-SiC for the same Ge content in the range high enough to meet the need of applications in the visible and the infrared regions.

By means of the multi-dimensional device simulator ISE, the feasibility of the new design is successfully tested. The simulation results show that the proposed power switch can be triggered by a near infrared laser beam. In comparison with devices based on the other polytypes of SiC[5], this device benefits from having fewer lattice mismatches between the SiCGe and 3C-SiC.

2 Structure design and light-activation principle

Figure 1 shows a cross section and the doping profiles of the light-activated Darlington transistor based on 3C-SiC. The device is actually a monolithic integration of the 3C-SiC Darlington transistor with a floating auxiliary emitter and a SiCGe/3C-SiC heterojunction photodiode that provides a primary base current induced by irradiation to trigger the Darlington transistor. An ITO electrode is employed as an interconnection between the photodiode and the auxiliary transistor, which are isolated from each other by a SiO_2 trench. The trench can be made using reactive ion etching (RIE)[6]. Sharing the same substrate as the Darlington transistor, the SiCGe/3C-SiC photodiode is formed by a hetero-epi-growth of the SiCGe layer directly on the n type 3C-SiC drift after the p base epi-growth and the n^+ emitter ion implantation processes have been completed. As an absorption layer, the SiCGe layer should be doped with a low concentration, however in order to get a good ohmic contact, its top layer must be heavily doped. A p-i-n type photodiode is designed to meet both of these requirements.

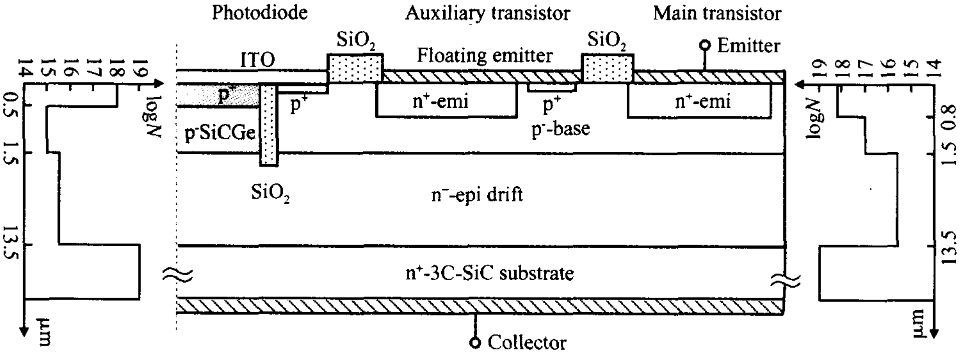

Fig. 1 Cross-section and doping profiles of the SiCGe/3C-SiC light-activated Darlington transistor

The most important parameters to the design and simulation of the heterojunction photodiode are the band gap and the optical absorption coefficient of the ternary alloy. Since the study of the growth of SiCGe on SiC is in its initial stage, the parameters required for accurate design and simulation are mostly unavailable at present. Therefore, we used Orner's calculation method[7] and the McFarlane-Roberts equation[8] to estimate the band gap and the absorption coefficient of the SiCGe with varied composition ratios. The details have been published elsewhere[9]. Accordingly, we choose a SiCGe with a band gap of 1.52eV to form the photodiode, which corresponds to an ideal composition of 30% Ge and 70% SiC.

In order to make the photodiode have a high enough optical responsivity, we choose a commonly used 0.63μm laser as the triggering light source. When the triggering light is introduced into the photodiode through the ITO, the light-generated electrons and holes in the SiCGe will be swept by the electric field in the space region, in which the light-generated holes are drawn into the p-base through the ITO, resulting in a photocurrent in the base. The auxiliary transistor is designed to be longer than the main transistor. When the photocurrent flows through the base, the base-emitter junction of the auxiliary transistor must be put into a forward biased status because of a large voltage across the auxiliary base region. Then the auxiliary transistor turns on, and its emitter current is introduced through the floating emitter contact into the base of the main transistor. The Darlington transistor is then turned on directly by light activation.

3 Simulation and analysis

Using the multi-dimensional simulation software ISE, we optimized the structure and parameters of the newly designed light-activated Darlington transistor. Lacking data for the SiCGe alloy, we have to assume that the SiCGe alloy with the proper Ge content has SiC-like properties except for its band gap and optical absorption. Models used in the simulation are concerned with mobility, saturation of drift velocity, effective intrinsic carrier density, band gap narrowing, Fermi-Dirac statistics, incomplete ionization, Auger and Shockley-Read-Hall recombination, and impact ionization. The temperature chosen for all the simulations is 300K.

A simulation plot of the photocurrent density versus incident light power density under a bias of 40V is shown in Fig. 2 for the SiCGe/3C-SiC hetero-junction photodiode of the Darlington transistor. The photocurrent is a linear function of the incident light power, which is nearly independent of the bias. The slope of the plot, i. e. the optoelectronic efficiency is about 88.9mA/W.

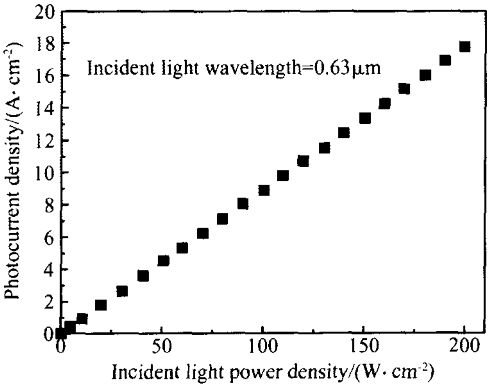

Fig. 2 Photocurrent density of the SiCGe/SiC photodiode versus incident light power

Figure 3 shows the light-activation characteristics of the Darlington transistor biased by 20 and 40V, respectively. We can see clearly that the light-activated device has a good switching characteristic demonstrated by a threshold incident light power similar to a normal Darlington switching transistor. The threshold triggering light power varies slightly with the collector voltage. For the demonstration design and simulation, the threshold light power changes from 13 to 12W/cm^2 when the collector voltage changes from 20 to 40V.

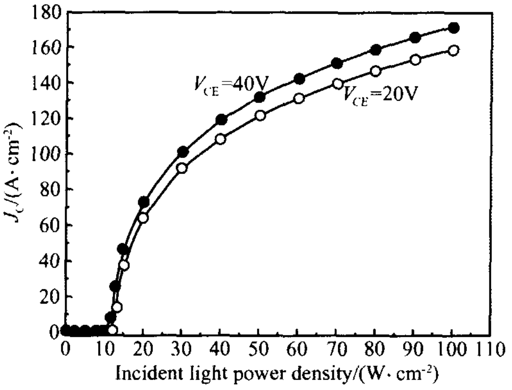

Fig. 3 Light-triggering characteristics of the SiC light-activated device

Figure 4 shows a plot of the common emitter current gain versus collector current density for the Darlington transistor at a collector voltage of 10V. According to the simulation result, a maximum current gain of about 890 may be achievable, which is high enough to amplify the photocurrent for light triggering.

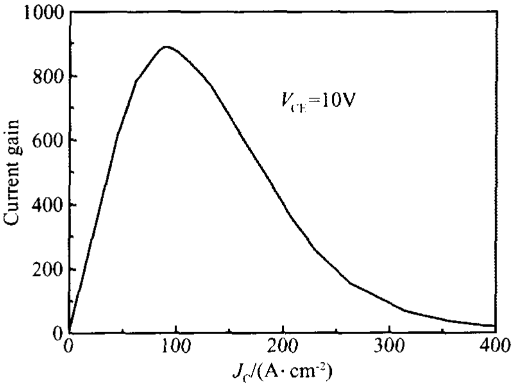

Fig. 4 Simulated common emitter current gain of the 3C-SiC Darlington transistor

The forward I-V characteristics of the SiC light-activated Darlington transistor are shown in Fig. 5 for different densities of the triggering light power. It can be seen that the turn-on voltage knee is around 4V and the output current capability depends on the incident light power, especially in the low power range. However, in the case of low output current, the same collector current can be obtained by triggering with a relatively low light power, as long as the collector-emitter voltage is high enough.

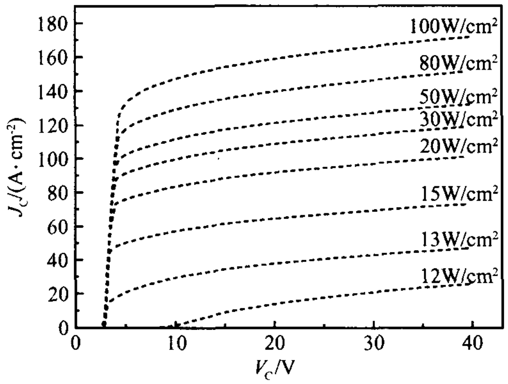

Fig. 5　I-V characteristics of the SiCGe/3C-SiC light-activated Darlington transistor

4　Summary

A new design for a SiC light-activated Darlington power transistor is proposed for easier fabrication. The new design needs only one hetero-epitaxial growth of SiCGe on 3C-SiC, and only a little lattice mismatch is added into the fabrication process compared to that of a normal SiC Darlington transistor. The feasibility of the new design is confirmed by the ISE simulation presented in this work. In comparison with similar designs based on the other polytypes of SiC, the new device benefits from having few lattice mismatches between the SiCGe and 3C-SiC. A maximum common emitter current gain of about 890 and superb light-activation characteristics may be achievable. The performance simulation demonstrates that the device has a good I-V characteristic with a turn-on voltage knee of about 4V.

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SiCGe/3C-SiC 异质结光控达林顿晶体管的设计与仿真*

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摘要：针对抗电磁干扰的需要提出了一种由 SiCGe/3C-SiC 异质结构成的光控达林顿晶体管设计. 用多维器件模拟软件 ISE 对这种新型功率开关进行了特性仿真. 结果表明，与采用其他结晶类型的碳化硅衬底相比，SiCGe 与 3C-SiC 间较小的晶格失配有利于提高器件性能，可使其最大共射极电流增益达到 890，获得最好的光触发特性和较好的 I-V 特性，饱和压降大约为 4V.

关键词：SiCGe；SiC；异质结；达林顿晶体管
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