Silicide/Strained $Si_{1-x}Ge_x$ Schottky-Barrier Infrared Detectors

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Abstract—**By employing a thin silicon sacrificial cap layer for silicide formation we have successfully demonstrated Pd_2Si/strained $Si_{1-x}Ge_x$ Schottky-barrier infrared detectors with extended cutoff wavelengths. The sacrificial silicon eliminates the segregation effects and Fermi level pinning which occur if the metal reacts directly with the $Si_{1-x}Ge_x$ alloy. The Schottky barrier height of the silicide/strained $Si_{1-x}Ge_x$ detector decreases with increasing Ge fraction, allowing for tuning of the detector's cutoff wavelength. The cutoff wavelength has been extended beyond 8 μm in $PtSi/Si_{0.85}Ge_{0.15}$ detectors. We have shown that high quantum efficiency and near-ideal dark current can be obtained from these detectors.**

I. INTRODUCTION

SINCE the concept of silicide Schottky-barrier detector (SBD) focal plane arrays (FPA's) was proposed by Shepherd and Yang [1] in 1973, the silicide/Si FPA has become the most mature technology for large-area, high-density FPA's for many short-wavelength infrared (SWIR, 1 to 3 μm) and middle-wavelength infrared (MWIR, 3 to 5 μm) applications. This is due primarily to their status as the only infrared imagers that are fabricated by well-established silicon VLSI processes [2], [3]. In recent years, IrSi SBD's [4] and $Si_{1-x}Ge_x$/Si heterojunction internal photoemission (HIP) [5], [6] detectors have been investigated to extend the application of silicon-based FPA's into the long-wavelength infrared (LWIR, 8 to 10 μm) spectral range. In the present work, we have demonstrated Pd_2Si/strained $Si_{1-x}Ge_x$ and PtSi/strained $Si_{1-x}Ge_x$ SBD's which offer an alternative approach for achieving LWIR operation.

The photodetection mechanism of a silicide SBD is based on the photoemission of holes from the silicide to the semiconductor; the cutoff wavelength is determined by the Schottky-barrier height. Strained $Si_{1-x}Ge_x$ on Si(100) has a smaller bandgap than silicon, with most of the band offset in the valence band [7], [8]. Thus, the Schottky–Mott model of metal–semiconductor contacts predicts that a silicide/strained $Si_{1-x}Ge_x$ junction will have a smaller p-type Schottky-barrier height and, therefore, a longer cutoff wavelength than will a silicide/Si junction. In initial efforts by Kanaya *et al.* in making silicide/$Si_{1-x}Ge_x$ devices [9], no reverse-bias electrical data or photoresponse was reported. Several later studies found that during the metal–$Si_{1-x}Ge_x$ reaction, palladium and platinum preferentially react with Si, resulting in Ge segregation [10], [11]. This creates defects that pin the Fermi level near midgap leading to a high Schottky barrier height [11]. In this study, by employing a thin silicon sacrificial layer for silicide formation on $Si_{1-x}Ge_x$, Ge segregation effects and Fermi level pinning have been eliminated, and reduced barrier heights and long-wavelength photoresponse have been obtained for Pd_2Si/strained $Si_{1-x}Ge_x$ and PtSi/strained $Si_{1-x}Ge_x$ detectors.

II. EXPERIMENT AND RESULTS

Our samples were grown by rapid thermal CVD on lightly doped p-type Si(100) substrates at 600–700°C [13]. The structure consists of a fully strained $Si_{1-x}Ge_x$ alloy layer on top of a strained graded composition $Si_{1-y}Ge_y(y: 0 \rightarrow x)$ layer. The graded layer prevents the formation of a parasitic hole barrier at the substrate/$Si_{1-x}Ge_x$ interface. The $Si_{1-x}Ge_x$ is capped by a thin sacrificial silicon layer (40–100 Å) which will be consumed later in silicide formation. After an oxide layer was deposited and windows were opened in this oxide, silicide was selectively formed inside these windows using standard e-beam evaporation and annealing processes. We have fabricated both $Pd_2Si/Si_{1-x}Ge_x$ and $PtSi/Si_{1-x}Ge_x$ detectors. In the palladium devices, the targeted silicon sacrificial layer thickness was 100 Å, and the deposited palladium was nominally 150 Å. In the platinum devices, the sacrificial layer was 40 Å, and the metal was 25 Å. The Si cap and deposited metal thicknesses were chosen so that the silicon sacrificial cap layer would be exactly consumed in the silicide formation process. This process ensures a Schottky contact with a pure silicide film (without Ge) and, at the same time, eliminates the Ge segregation at the interface which could cause Fermi level pinning.

Fig. 1(a) shows the measured Fowler plots for three $Pd_2Si/Si_{1-x}Ge_x$ ($x = 0$, 0.20, 0.35) detectors using a Fourier transform infrared (FTIR) spectrometer at 77 K. The cutoff wavelength clearly increases with increasing

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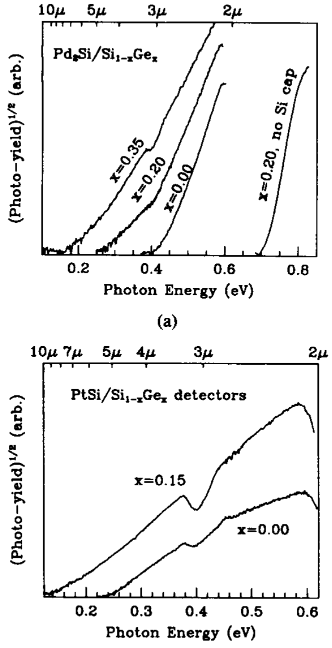

(a)

(b)

Fig. 1. Infrared photoresponse at 77 K of (a) $Pd_2Si/Si_{1-x}Ge_x$ and (b) $PtSi/Si_{1-x}Ge_x$ Schottky-barrier detectors. The cutoff wavelength gives the barrier height of the corresponding silicide/$Si_{1-x}Ge_x$ Schottky junction. (The dip at 400 meV in some of these spectra (e.g., (b)) is due to artifacts of the measurement instrument, although the kinks ($Pd_2Si/Si_{0.80}Ge_{0.20}$) at ~400 meV are real.)

Ge fraction for the $Pd_2Si/Si_{1-x}Ge_x$ detectors as expected. Note that when no silicon sacrificial layer was used for silicide formation, a higher barrier height was obtained, presumably due to the Ge segregation and consequent Fermi level pinning (Fig. 1(a)). This is the first time such a Si cap layer was used to avoid this parasitic effect. The conventional Pd_2Si/p-Si Schottky diode has a barrier height of 420 meV, which gives a cutoff wavelength of 3 μm. As Ge is introduced, the cutoff wavelengths of the $Pd_2Si/Si_{0.8}Ge_{0.2}$ and $Pd_2Si/Si_{0.65}Ge_{0.35}$ detectors have been pushed to about 5 and 7.5 μm, which correspond to barrier height reductions of 160 and 250 meV, respectively. The kink around 400 meV in the photoresponse curves of the $Pd_2Si/Si_{0.80}Ge_{0.20}$ and the $Pd_2Si/Si_{0.65}Ge_{0.35}$ detectors is thought to be due to a parasitic barrier in the valence band resulting from unconsumed sacrificial silicon with a thickness on the order of 1 nm or less [14]. While this thin parasitic Si barrier adversely affects the injection efficiencies of the photoexcited holes, it does not change the apparent cutoff wavelength of the device [14].

From a simple extrapolation of the measured barrier heights as a function of alloy composition, we found that a Ge fraction of more than 0.40 is required in order to have a cutoff wavelength beyond 10 μm in a $Pd_2Si/Si_{1-x}Ge_x$ detector. Since the $Si_{1-x}Ge_x/Si$ is not a lattice-matched system, it is desirable to use as little Ge as possible in the silicide/$Si_{1-x}Ge_x$ detectors to minimize problems associated with strain in this system. Platinum silicide has a lower barrier height to p-type silicon than does the palladium silicide (240 versus 420 meV). Therefore, it is expected that the same cutoff wavelength can be achieved in the $PtSi/Si_{1-x}Ge_x$ detectors with a lower Ge fraction. The spectral response of a $PtSi/Si_{0.85}Ge_{0.15}$ detector is shown in Fig. 1(b) along with that of a PtSi/Si control device. The cutoff wavelength is extended from 5.2 to 8.8 μm with only 15% Ge in the alloy, corresponding to a barrier height reduction of 100 meV. By extrapolation, a cutoff wavelength beyond 10 μm is expected for a $PtSi/Si_{1-x}Ge_x$ detector with as little as 18% Ge in the alloy.

The observed barrier height reductions are in reasonable agreement with those predicted by the simple Schottky model. Our experimental values for the Pd_2Si and PtSi devices are 7.4 and 6.7 meV/atomic %Ge, respectively, compared to 7.4 meV/atomic %Ge for the valence band offset at a strained $Si_{1-x}Ge_x/Si$ interface [7], [8]. This agreement indicates that the partial substitution of Si with Ge on the semiconductor side of a silicide/Si contact does not have a significant effect on the distribution of the interface states and tail states, which could affect the barrier height reductions.

The reverse leakage levels in these silicide/$Si_{1-x}Ge_x$ detectors were examined in the temperature range of 90–250 K. Fig. 2 shows the temperature-dependent leakage currents of four different devices at 2-V bias (actual I–V curves can be found in [12]). By fitting the temperature-dependent dark current data with thermionic emission theory, we obtained barrier heights in good agreement with those found from photoresponse measurements, indicating near-ideal low leakage levels.

The measured external responsivities (40 K) of the $PtSi/Si_{0.85}Ge_{0.15}$ detector and the PtSi/Si control device are shown in Fig. 3 (filled triangles and squares). Because of the limited range of the monochromator used, accurate measurement beyond 4 μm could not be obtained, and the results of the spectral responses measured by FTIR at 77 K were scaled to match the responsivities obtained with the monochromator around 4 μm to give the full responsivity curves. The $PtSi/Si_{0.85}Ge_{0.15}$ detector offers superior responsivity to the conventional PtSi/Si detector over the whole wavelength range. The $PtSi/Si_{0.85}Ge_{0.15}$ detector has peak responsivity of 0.1 A/W at 2.5 μm, which is 2.5 times higher than that of the PtSi/Si control device. It is also comparable to the highest reported responsivities found in $Si_{1-x}Ge_x/Si$ HIP detectors [5], [6]. This enhanced quantum efficiency of the $PtSi/Si_{1-x}Ge_x$ detector over that of the PtSi/Si device may be primarily due to the reduced barrier height.

In the standard PtSi/Si array process, the platinum silicide is selectively formed in active areas after all the high-temperature CMOS processes (for readout circuitry) are completed [2]. Modifying this process flow for the $PtSi/Si_{1-x}Ge_x$ detectors requires only one extra process step, the low-temperature epitaxial growth of the $Si_{1-x}Ge_x$ alloy layers and the Si sacrificial cap layer, before the PtSi

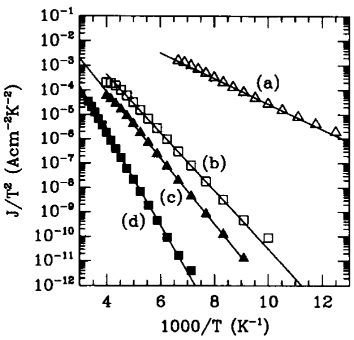

Fig. 2. Temperature-dependent dark current densities of $\mathrm{Pd_2Si/Si}_{1-x}\mathrm{Ge}_x$ and $\mathrm{PtSi/Si}_{1-x}\mathrm{Ge}_x$ detectors at 2-V reverse bias: (*a*) $\mathrm{PtSi/Si_{0.85}Ge_{0.15}}$, $\phi_B = 103$ meV; (*b*) PtSi/Si, $\phi_B = 236$ meV; (*c*) $\mathrm{Pd_2Si/Si_{0.80}Ge_{0.20}}$, $\phi_B = 269$ meV; and (*d*) $\mathrm{Pd_2Si/Si}$, $\phi_B = 379$ meV.

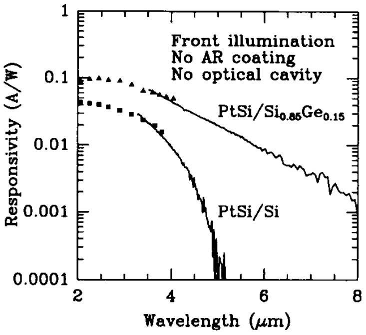

Fig. 3. Comparison of measured external responsivities of $\mathrm{PtSi/Si_{0.80}Ge_{0.15}}$ and PtSi/Si infrared detectors. Points represent data obtained with a calibrated infrared monochromator (40 K), while lines are scaled results from FTIR measurements.

formation. Since this step is done at 600–700°C, the CMOS circuitry will not be adversely affected, and since subsequent back-end steps are at low temperature, strain relaxation of the $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ should not be a concern. Therefore, fabrication of these detectors should be compatible with standard FPA technology.

III. SUMMARY

In summary, we have demonstrated for the first time $\mathrm{Pd_2Si/Si}_{1-x}\mathrm{Ge}_x$ and $\mathrm{PtSi/Si}_{1-x}\mathrm{Ge}_x$ Schottky-barrier long-wavelength infrared detectors. A silicon sacrificial layer was used to eliminate Ge segregation and Fermi level pinning. The cutoff wavelength is tunable by the amount of Ge: cutoff wavelengths over 8 μm have been obtained, and extension to > 10 μm should be straightforward. Ideally low leakage currents have been measured and an external responsivity of 0.1 A/W at 2.5 μm was obtained in the $\mathrm{PtSi/Si_{0.85}Ge_{0.15}}$ detectors, 2.5 times higher than that of the PtSi/Si control devices.

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