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Microcharacterization and Novel Device Applications of Semiconductor-Metal Eutectic Composites

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Semiconductor-metal eutectic composites, such as Si-$TaSi_2$, which consist of an aligned array of metallic rods permeating a semiconductor matrix, are electronic materials that offer a variety of novel device applications. These are, for example, high-power transistors, which are operated by manipulating the depletion zones of 3D arrays of Schottky junctions with the application of an external bias, and photodiodes and photodiode arrays that offer a nearly constant high quantum efficiency of at least 50% between 0.4 and 1 μm.

1. INTRODUCTION

Until very recently, because of the difficulties in obtaining single-crystalline materials, there was only a very limited effort in growing semiconductor-metal eutectic composites.[1)2)3)] These novel electronic materials, such as Si-$TaSi_2$, obtained by directional solidification of eutectic mixtures, consist of an aligned array of metallic rods ($TaSi_2$) permeating a semiconductor matrix (Si). Thus, a composite system containing three-dimensional (3D) arrays of Schottky junctions is obtained. The presence of these junctions offers a variety of novel volumetric device applications. As will be demonstrated here by using charge-collection scanning electron microscopy, the depletion zone widths of the *in situ* rectifying junctions in such a system can be controlled so that a desired depletion of a semiconductor matrix is obtained. This property of the material suggests its utilization in a novel Semiconductor-Metal Eutectic Transistor (SEMET), which is a bulk device offering, for example, a high-power device application. The presence of a large number of rectifying junctions (of the order of 10^6 cm^{-2}) also offers applications of these materials as photodiodes and photodiode arrays with high quantum efficiency in the wavelength range between 0.45 and 1 μm.

2. EXPERIMENTAL

The Si-$TaSi_2$ eutectic composite crystals were grown by the Czochralski crystal growth technique (for details, see reference 4). Eutectic composites contain about 10^6 $TaSi_2$ rods/cm^2 embedded in a single-crystalline Si matrix. Our earlier EBIC studies[5)] indicate that the $TaSi_2$ rods are continuous and oriented parallel to the growth direction with a maximum divergence of about 6°. The rods with an average diameter of about 1 μm and average interrod spacing of about 8 μm are arranged in a semi-random cellular structure with an average interrod spacing along the wall of about 4 μm. The Si matrix contains of the order of 10^{15} cm^{-3} of phosphorus. An ideal microcharacterization method for such a composite is the charge-collection scanning electron microscopy, also known as electron-beam-induced current (EBIC). The details of the EBIC studies of such a system were published recently.[5]

3. RESULTS AND DISCUSSION

Figure 1 presents EBIC images which show that the application of a reverse bias voltage to the metal rods causes the depletion zones to expand and eventually overlap. It should be emphasized here that the EBIC analysis of the depletion zone expansion as a function of the reverse bias provides the only reliable carrier concentration of the Si matrix. Our comparison measurements of the Hall effect and the EBIC on similar samples indicate that for low carrier concentrations (i.e., the unbiased depletion zone widths are large), narrowing of the interrod channels impedes transport, resulting in a significant underestimation of carrier concentration derived from the Hall effect data.[4]

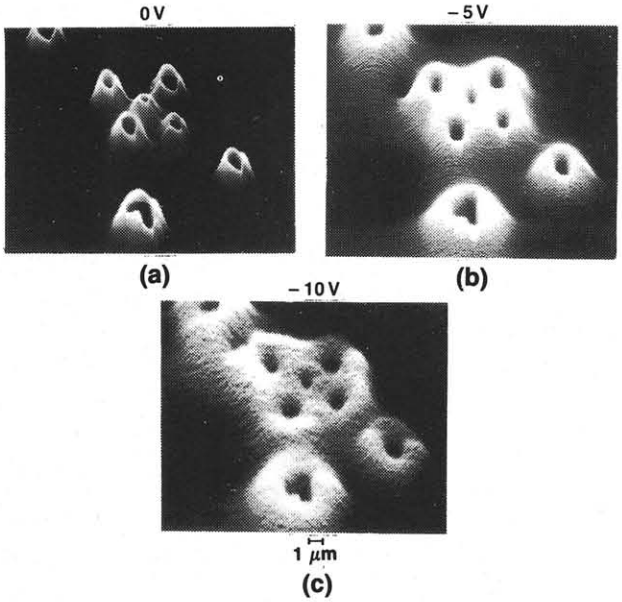

Fig. 1. Y-modulation EBIC images of the portion of the Si-$TaSi_2$ eutectic diode: (a) unbiased, (b) at a reverse bias of 5 V, and (c) at a reverse bias of 10 V.

The ability to control the depletion zone width with the application of the reverse bias suggests the utilization of the composite in a novel Semiconductor-Metal Eutectic Transistor (SEMET). Figure 2 illustrates the portion of the SEMET utilizing concentric rings for both the source and the gate with the drain dot in the center. The gate contact is formed by the formation of $CoSi_2$ film, which acts as an ohmic contact to the gate rods and as a rectifying contact to the semiconductor matrix. An evaporated Au-Sb film was used to form the contacts to the source and the drain. Figure 3 presents characteristics of a Si-$TaSi_2$ SEMET, which readily blocks a drain voltage of 240 V, and which failed at 325 V. The carrier concentration, derived from the EBIC measurements, of the Si matrix in the case is 2×10^{15} cm^{-3}, and the thickness of the device is 250 μm. It should be noted that the avalanche breakdown for a planar one-sided abrupt junction with a similar carrier concentration is expected at a lower value (i.e., 190 V). Thus, in SEMET, the avalanche breakdown is delayed as compared to the planar device. Computer simulation modeling of the SEMET indicates that the most probable cause of this behavior is the interaction of the depletion zones around the gate rods with those between the gate and drain. The latter floating rods may act in such a way as to hold the effective electric field at the gate rods, and thus delay the breakdown voltage.

In order to explore the factors affecting the high-voltage capability of such a device, the effect of the thickness of the device was considered. First, we measured a thick (500 μm) device which failed at 50 V. This was thinned down to 250 μm and retested, showing breakdown voltage of 350 V. Finally, the sample was thinned to 125 μm, and, in this case, the device operated at 600 V, which is three times larger than that expected for a conventional device of the same carrier concentration. The effect of thinning is most probably related to the divergence of rods. Thus, some rod extensions below the

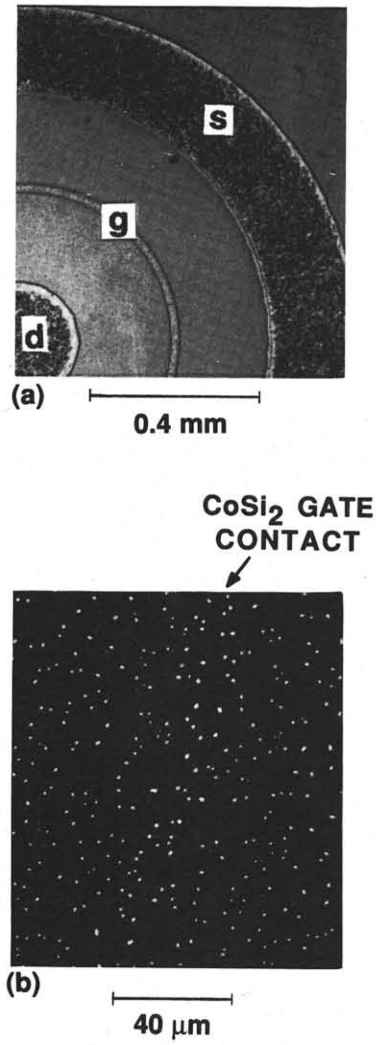

Fig. 2. (a) A section of the Si-TaSi$_2$ SEMET showing the source s, the gate g, and the drain d contacts; (b) a magnified image of the gate ring showing the distribution of the TaSi$_2$ rods.

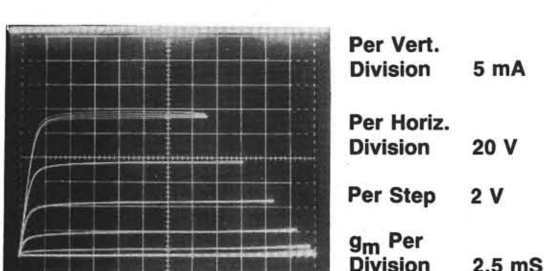

Fig. 3. Characteristics of a Si-TaSi$_2$ eutectic composite transistor.

gate and drain contacts may be separated closer on the back side (which was thinned) than on the side with the contacts. For thinner devices, the back-side gate-to-drain separation increases, resulting in the higher drain voltage.

The semiconductor-metal eutectic composite can also be used as a vertical, multijunction photodiode. In this case, when the rods are oriented perpendicular to the plane of the device, (i) the maximum distance that minority carriers have to travel to the nearest junction is small (i.e., the average interrod spacing), and (ii) this maximum distance does not change with the thickness of the device. The latter is an important property of the composite system, resulting in a nearly constant high quantum efficiency of a least 50% in the wavelength range between 0.45 and 1 μm. Figure 4 shows spectral sensitivity of a SiTaSi$_2$ photodiode. In addition, compared to the common planar Si photodiodes, the quantum efficiency in this case in the near infrared is high. Closely spaced junctions in this system may also provide high-speed response photodiode arrays with high spatial resolution and low crosstalk.

In summary, novel device applications of the semiconductor-metal composites are demonstrated. In addition to this and other Si-based systems, GaAs-based composites, for example, GaAs-MoAs and GaAs-CrAs systems, can be grown. The latter materials could provide interesting applications in optoelectronic devices.

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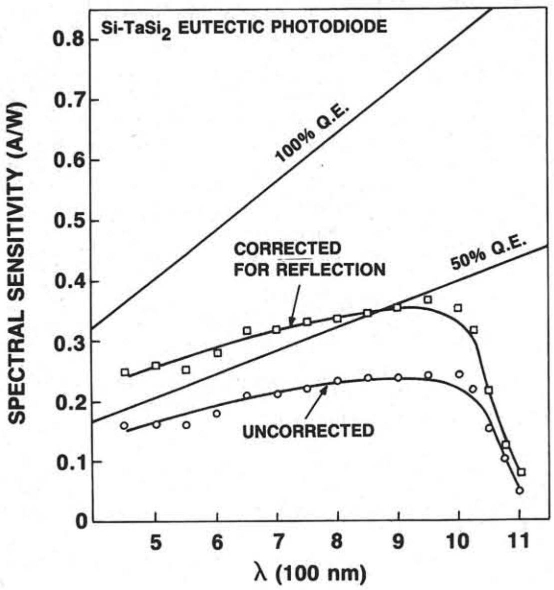

Fig. 4. Spectral sensitivity of a eutectic photodiode.

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