3130

An Electrically Driven Solid State Modulator

Suresh Uppal, Harvey N. Rutt
Optoelectronics Research Center, University of Southampton
Southampton, SO17 1BJ

Abstract

Simulation results for the design and fabrication of an electrically driven solid state modulator are presented. The design criteria has identified various trade-offs in the manufacturing of an electrically driven modulator using a p-i-n diode to be made from high purity Ge. The issues relating to the doping, layer thickness and contact material for the diode fabrication are discussed. A compromise between the high 'ON' state transmission and uniformity is required to achieve the optimum performance from the device. Using FEMLAB and ATLAS a p-i-n diode with different apertures has been simulated which clearly show the effects of non-uniformity and the requirement of a mesh-type electrode for a uniform absorption across the large device apertures.

Keywords: infrared, p-i-n diode, solid-state modulator, High purity Ge

Introduction

Infrared imagers using pyroelectric detectors require optical modulation which is currently achieved using a rotating chopper blade. This, however, introduces mechanical components in the system making it bulky at the same time affecting the image quality during camera motion. An electrically driven modulator however can overcome these problems. Such a modulator can also be used for built in calibration or 'thermal referencing', and for providing variable IR transmission in situations where mechanical solutions are undesirable.

A solid -state IR modulator should be capable of using the entire 8-14 micron optical band, with high "ON" and low "OFF" state transmission over a large aperture (typically 1cm^2). In addition it should be polarisation insensitive, compact, and capable of incorporation into low F-number systems along with low power consumption. Acousto-optic, electro-optic and reflection modulators using plasma frequency effects in semiconductors and even LCD devices have been investigated as methods of modulating IR beams but cannot fulfil all the requirements. Using a novel method of introducing excess carriers in suitably prepared Ge, adequate modulation has been achieved in the 8-14 micron [1] region. Based on this method an optical modulator has been successfully fabricated [2]. However, the optical modulator uses expensive laser diodes and wastes a lot of laser power. Non-uniform illumination, high power dissipation and non-availability of an antireflection coating in both near and mid IR range are other issues with optical based modulator. A low power electrical modulator, however, will use applied bias to inject carriers avoiding inefficiencies of laser sources.

Material requirement

To make an electrically driven solid state modulator for the IR range we shall require a semiconductor material which is IR transparent in the 8-14 micron range, indirect band gap with strong sub-band transitions in the IR range, and has high carrier mobility and long carrier life times. The requirement for inter sub-band transitions arises because classical free carrier Drude-Zener absorption is too weak for a practical device. The availability of suitable dopants/coatings and ease of fabrication are additional constraints. Germanium possesses the properties of being an indirect band gap material with IR transparency and interband transitions in the required spectral region of 8-14 microns. It is readily available in high purity for use in nuclear detectors and possesses long carrier lifetimes and high carrier mobilities.

Figure 1 shows the band diagram of Ge and the absorption spectra of intrinsic and p-type Ge. The transitions between the light and heavy hole band in the valence band of Ge are the desired interband transitions in the mid IR.

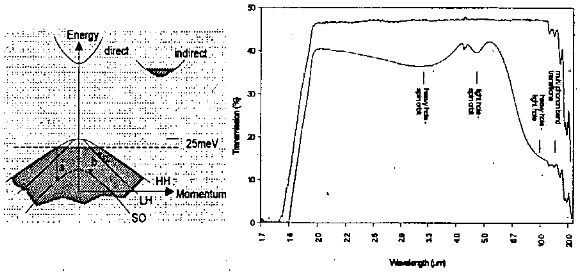

Fig 1: The band diagram of Ge (left) showing a) heavy hole to spin orbit b) light hole to spin orbit and c) heavy hole to light hole transitions. The corresponding absorption spectra for intrinsic (top) and p-type Ge is shown on the right.

Design Criteria

A simple p-i-n diode based modulator is shown in Fig.2.

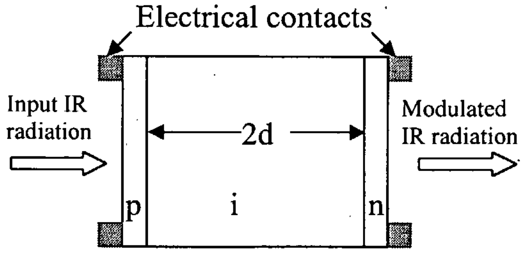

Fig 2: A simple p-i-n diode modulator

The modulator optically ON (Electrically OFF) state transmission is given by

$$T_{on}= T_0 \exp -(N_p*x_p*\sigma_h),$$

where $T_0=1$ for 100% transmission, σ_h is the hole absorption cross-section ($5.33 \times 10^{-16} cm^2$), N_p is the doping density for holes ($/cm^3$) of the p-region, and x_p is the p-region thickness. In the optically OFF (electrically ON) state the absorption occurs in the p as well as i-regions and hence the transmission is given by

$$T_{off}= T_0 \exp -(N_p*x_p*\sigma_h) \exp (- n_p*\sigma_h),$$

where n_p is the injected hole density ($/cm^2$) and can be given by $n_p=\int_0^r c_p(x)dx$, where c_p is the hole concentration in the i-region for the Forward Biased (electrically ON) diode and r its thickness.

For a high optically ON state transmission we shall require the product of N_p and x_p to be the low. On the other hand for a low optically OFF state transmission we shall require maximum n_p (absorption from the p-layer is fixed). In this state, for a uniform current injection we also need a low resistance 'p' layer which requires a high doping density.

Plotting T_{on} for zero n_p, optically ON, as a function of doping density of p layer gives us the acceptable limit for the doping of the p-layer as shown in Fig.3. This graph suggests that for a 95% transmission in the ON state we shall require a 'p' area doping density of ~1×10^{14} /cm².

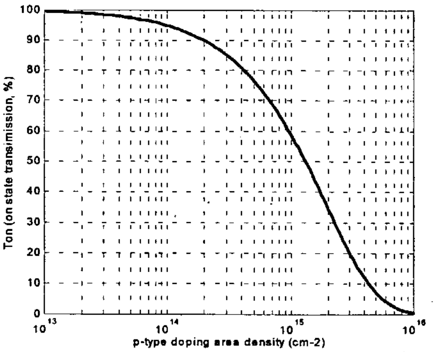

Fig 3: Ton Vs doping density of p-layer

Using the theory of a p-i-n diode, the hole area carrier density in the intrinsic region is given by T_a*J/q where T_a is the ambipolar life time of carriers, J is the forward current density in A/cm^2 and q is the electric charge. Thus a high carrier life time is essential. From the theory, we can also predict the optimum range for the thickness of the i-layer. The voltage drop as a function of normalised intrinsic region length is shown in Fig. 4. A long i region (2d>L_a, L_a is the ambipolar diffusion length) means a large voltage drop in the i-region, a short i-region (2d<L_a) means recombination occurs in the heavily doped end regions. Therefore the thickness of the intrinsic region is selected such that 2d~L_a.

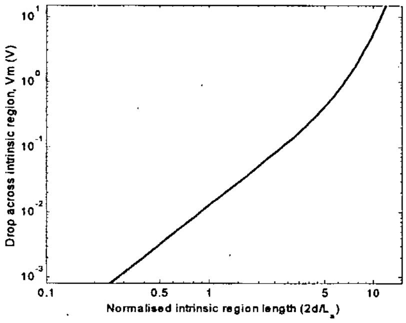

Fig 4: Voltage drop against the i-region length decides that optimum length of the I region is where 2d~La.

Device simulation results

The simulations for the p-i-n diode structure have been performed using FEMLAB as well as ATLAS, a device simulation software from SILVACO [3]. A FEMLAB simulation structure is shown in Fig.4.

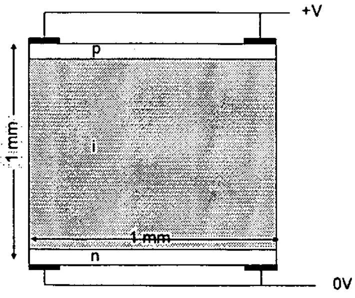

Fig 4: The FEMLAB simulation structure

For this device, Ge material parameters were taken. A Gaussian shaped diffusion profile was assumed for both p and n-type dopants. The model was solved for various voltages. A cross-section of the hole concentration at a depth of 0.5 mm is shown in Fig. 5.

It can be seen from the hole concentration profile that a non-uniformity exists across the diode depth as the device size increases. This non-uniformity becomes worse for a 2.5mm and larger devices. Since the hole concentration appears as exponential in the expression for transmission, even a small hole variation across the depth leads a very high value of non-uniformity in the transmission from the structure.

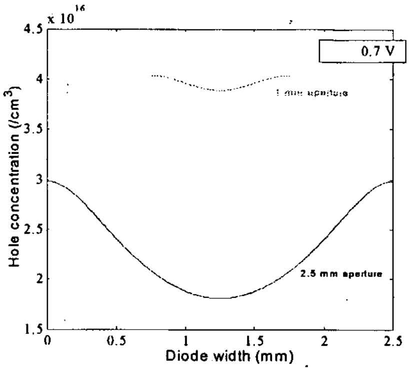

Fig 5: Hole concentration Vs diode width for a diode of 1mm aperture.

Using ATLAS, similar results were obtained. However, in ATLAS, the mobility was also made a function of the concentration. Using same parameters as used in FEMLAB simulations, but modifying the simulation structure to incorporate additional electrode help reduce the non-uniformity problem.

The above analysis demonstrates the need for a highly optimised electrode mesh to avoid non-uniformities in the transmission within the device structure, for large device apertures.

Process simulation results

Attention has been paid to recognising the potential p and n-type dopants, thermal processing cycles and contact material for fabricating the p-i-n device using HPGe. One of the main constraints for device processing is to keep the material away from contamination to maintain a high carrier lifetime of the high purity material. This requires careful handling of material and least processing steps to avoid contamination. Cu, Fe etc are the main impurities to avoid since they have a large diffusion coefficient even at room temperature and they introduce deep levels in the band gap thereby drastically reducing the carrier lifetimes. This means that we should avoid unnecessary high temperature steps wherever possible.

Since ion-implantation is a room temperature method to introduce dopants and we can control the amount of dopant, it seems the best choice for doping. Also ion-implantation is regularly used in present day Si technology and hence is readily available. As noted above, an area doping density $(N_p * x_p)$ of ~1e14/cm^2 for high T_{on} means that for a volume doping density (N_p) of ~1e17 /cm^3, one needs x_p of the order of 10 microns. A higher value of N_p would degrade the carrier mobility. Among the p-type dopants Boron seems to be good choice since it is a light element and therefore can be implanted to large depths at sensible implantation energies. A theoretical 300 keV Boron implantation profile is shown in Fig.7.

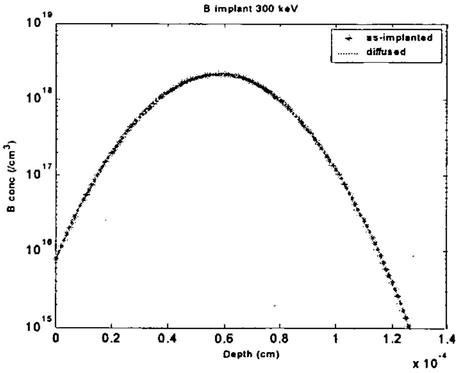

Fig.7: Theoretical as-implanted (B @300keV with 1e14 /cm^2) and diffused (700C, 60mins) profile. The diffused profile shows no movement as a result of the very low diffusion coefficient.

Also, Boron is known to self-activate in Ge after implantation, thus avoiding the need for high temperature electrical activation step. However, it has very slow diffusion coefficient as compared to other p-type dopants [4] hence may require variable high energy implantation in the MeV range.
Other p-type dopants such as Ga and In are also being considered and require further investigation.

The diffusion coefficients for n-type dopants in Ge are much higher than p-type dopants. Usually activation annealing is also required after implantation. Fig. 7 shows that even moderate temperature but small time annealing is effective in achieving good electrical activation and diffusion. Thus a low energy, high dose implantation can be used to obtain required doping profiles for n-type dopants in Ge.

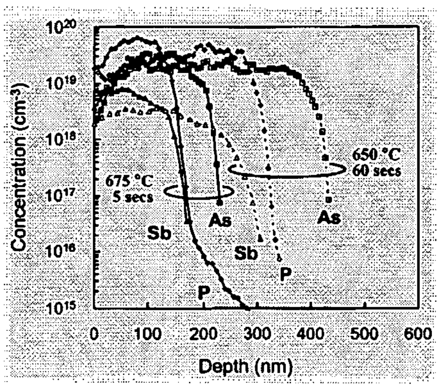

Fig 8: Spreading resistance profiles for n-type dopants in Ge after Rapid Thermal Annealing. Good electrical activation can be achieved with brief annealing times at moderate temperatures (from Ref. 5).

It is very important to obtain low resistance ohmic contacts to the p-i-n device. To avoid a rectifying contact it is essential to choose a metal that has higher work function than p-type semiconductor and lower that n-type semiconductor surface. It has been suggested that amorphous Ge can be used as contact material. However, for our application there are no major advantages of using amorphous Ge layer. This process adds an extra step in diode fabrication. Ideally, direct soldering to Ge should be chosen if possible as this avoids extra (high temperature) processing steps e.g. metal evaporation etc. Using the same 'type' dopant for electrode formation as used in bulk is likely to cause a heavy same type doping in the very near region of electrode thereby increasing the potential barrier to the minority carrier. A doped solder say Sb doped for n-type and In or Ga doped for p-type may be used. The literature also suggest metals like Ni, Cr, and Ti being used for contact electrodes but one has to be extra careful so as to not perform any high temperature steps after their deposition as these metals diffuse quite fast and kill carrier lifetime by introducing deep levels in the band gap.

Future Work

In the coming months the simulation will continue to predict device behavior with a focus on 3-d modeling. Process simulation is being carried out to predict precise dopant distribution after thermal processing. Suitable dopants/ layer thicknesses shall be available from the simulations and will be incorporated in the process simulation. It is planned to fabricate first a small area p-i-n diode with suitable ohmic contacts and characterize it for modulator performance.

REFERENCES

1 Rutt, HN, Manning PA, Donohue, PP, 1996, International Patent, PCT/GB96/02221

2 Fairley, PD, 2000, PhD thesis, University of Southampton

3 ATLAS user manual, ver. 5.8.4.R, Silvaco International, Santa Clara, USA

4 Uppal S, Willoughby, AFW, Bonar, JM, Cowern, NEB, Grasby, T, Morris, RJH; Dowsett, MG, 1996, J. Appl. Phys., **96**, 1376-1380

5 Chui, CO, Gopalakrishnan, K, Griffin, PB, Plummer, JD, Saraswat, KC, 2003, J. Appl. Phys., **83**, 3275-3277

ACKNOWLEDGEMENTS

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence.