Recombination Properties of Diode Structures by Study of Thermal Emission Beyond the Fundamental Absorption Band

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Abstract. The study presents the possibilities of applying the measurement of spatial and temporal distribution of thermal radiation of a \textit{p-n} junction structure located in a homogeneous temperature field higher than the ambient temperature, modulated by the presence of excess carriers injected through the junction, to determine surface recombination velocity at the injecting contact of the diode emitter and to measure the diffusion length in the base. Good agreement was obtained between the experimental results and calculations based on solutions of the transport equations.

1. Introduction
Performance of \textit{p-n} junction based semiconductor devices (like light modulators and emitters) strongly depends on recombination activity of injection structure elements. We show how mapping the spatial and temporal output of thermal emission (TE) escaping a diode base in the spectral band of free carrier absorption makes it possible to determine such major parameters of the injection process as the effective diffusion length ($L$) or effective carrier lifetime ($\tau$) in the base and the carrier recombination velocities at the \textit{p-n} junction and ohmic contact planes, $s_1$ and $s_2$ respectively.

2. Research methodology
A 5.0 mm-long \textit{p$^+\text{-}n\text{-}n^+$} germanium structure (figure 1) was taken as a source of infrared thermal emission following free carrier injection and recombination in the structure base.

\textbf{Figure 1.} Image of bulk $n$-Ge based diode with junction on the left and ohmic contact on the right. All free planes are polished and etched. Thermal imaging camera maps the upper plane.
Parameters of current-induced TE output beyond the fundamental absorption band (λ > 2 µm) are related to the base absorption coefficient with the latter being dependent on the concentration of injected free carriers (∆p). TE maps were recorded in continuous (I = 0.5 A, 2D spatial distribution of injected carriers when bias current is on, figure 2) and pulsed (I = 1 A, 200 µs pulse duration) modes with 8-12 µm thermal imaging camera. To fix the temporal evolution of free carriers in the base due to recombination processes, experimental TE maps were recorded at 50, 100, 180, 380 and 580 µs after a bias current is off (figure 3). To have ten times increase of the signal to noise ratio, the study was performed at T = 750°C.

3. Results of measurements and calculations

The 2D distribution of thermal emission output (figure 2) evidences low impact of free carrier recombination at base plane and makes one dimensional approximation valid. Experimental ∆p(x,t) distribution (figure 3) clearly shows permanent free carrier density decrease due to diffusion and recombination at the ohmic contact for all time delays and still growing impact of this recombination at ∆t > 50 µs. The position of maximum concentration region shifts toward ohmic contact when time delay increases. By matching experimental and theoretical results at ∆t = 100 µs, we obtained following fitting parameters: Lh = (Dhτ)1/2 = 950 µm, s1 = 180 cm/s, s2 = 300 cm/s.

Assuming the following simplified relation between injected hole concentration and distance x from the p-n junction plane:

\[ \Delta p(x) = \Delta p_0 \exp\left(-\frac{x}{L_h}\right) \]  

where \( \Delta p_0 \) is the hole concentration at the junction plane, we obtain carrier concentration distribution determined by the value of electric current and the diffusion length \( L_h \). Inserting this distribution into the formula for emissivity \( \varepsilon \) and assuming that the absorption coefficient \( \alpha(x) = \sigma \cdot \Delta p(x) \), where \( \sigma \) is the cross-section for holes (its value equal to 1.0⋅10^-16 cm^2 was assumed, taking into account the spectral range of the camera), we obtain the distribution of thermal radiation intensity along the base of the p-n diode using the following relation:

\[ \varepsilon(x) = \frac{(1-R)(1-\exp(-\alpha(x)d))}{1-\exp(-\alpha(x)d)} \]  

Figure 2. Static thermal emission power map of the diode base (junction is on the left) shown in false colours with red related to higher value. Thermovision images of the structure base, recorded for currents 1A (figure 2A) and 0.5A (figure 2B), at structure temperature 75°C. The upper part of figure 2B shows the uniform temperature distribution on a blackened part of the base. The range of observed changes for thermal radiation intensity in the non blackened part (from the left to the right) correspond to the apparent change of temperature equal to about 10°C.
Taking into account also minor components of the registered radiation (reflection and transmission), depending on the method of measurements, we calculate a theoretical profile of the thermal radiation of the diode base. Figure 4A shows theoretical changes in the distribution of thermal radiation intensity along the base depending on the current value. For low current densities (curve c) this profile is close to the exponential profile, and differs from it at current densities close to the limiting emissivity (1-R) (curves a and b). At high injection levels the entire base of the p-n structure reaches the limiting emissivity. Normalizing the theoretical profile \( P(x) = W_b \varepsilon(x) \), with \( W_b \)- blackbody total radiant emittance) to unity and comparing it with the experimental profile of the emissivity changes \( \Delta P \) (curve 1 in figure 3), we can fit both profiles by fixing the parameter \( L_h \). The result of such fitting is shown in figure 4B.

In order to calculate the surface recombination velocity at the rectifying contact we will use the measurements of the thermal radiation distribution along the base at 180, 380 and 580 \( \mu \)s time intervals after bias current is turned off, shown in figure 3. These distributions are chosen to allow comparison at low injection levels, where emissivity function is closer to linear.

Spatial distribution of injected holes between the contacts, \( \Delta p(x,t) \), and its evolution in space and time were obtained from the solution of the continuity equation:

\[
\frac{\partial \Delta p(x,t)}{\partial t} = D_h \frac{\partial^2 \Delta p(x,t)}{\partial x^2} - \frac{\Delta p(x,t)}{\tau}
\]  

(3)
with boundary conditions:  
\[ D_h \frac{\Delta p}{dx} = s_1 \Delta p \ (x = 0), \]  
\[ D_h \frac{\Delta p}{dx} = -s_2 \Delta p \ (x = w) \]  
where \( D_h \) is the free hole diffusion coefficient, \( s_1 \) and \( s_2 \) are the carrier recombination velocities at the junction and ohmic contact planes, respectively, \( w \) – the base thickness and \( \tau \) – the bulk carrier lifetime in the base region. The analysis of the turn-off transient of \( p-n \) junction diode was given by R.H. Kingston (see in [3]). The following analytical solution for surface carrier generation, obtained with a multimode method shown in [4], was used for the purposes of the calculations:

\[ p(x, t) = 2H \exp \left( \frac{-t}{\tau} \right) \sum_{i=1}^{\infty} \sin \alpha_i \frac{\sin \left( \frac{\lambda_i x}{w} + \alpha_i \right)}{w + D_h \left( \frac{\cos \alpha_i^2}{s_1} + \frac{\cos \beta_i^2}{s_2} \right)} \exp \left( -\frac{(\lambda_i)^2 D_h t}{w^2} \right) \]  

with:

\[ \lambda = i \pi - \arctan \left( \frac{D_h \lambda}{s_1 w} \right) - \arctan \left( \frac{D_h \lambda}{s_2 w} \right), \]

\[ \alpha_i = \arctan \left( \frac{D_h \lambda_i}{s_1 w} \right), \quad \beta_i = \arctan \left( \frac{D_h \lambda_i}{s_2 w} \right) \]

where \( H \) – the number of carriers per surface generated directly before the bias current is turned off.

Theoretical distribution of the carrier concentration along the base (the junction is on the left) calculated (in sequence from the top) at 180, 380 and 580 \( \mu \)s time delays after bias current is off, \( L_h = 950 \ \mu \)m, \( D_h = 42 \ \text{cm}^2/\text{s} \) is shown in figure 5.

\[ \text{Figure 5. Theoretical distribution of the carrier concentration along the base (the junction is on the left) calculated at (a) 180, (b) 380 and (c) 580 \( \mu \)s time delay after bias current is off. Fitting parameters } s_1 = 180 \ \text{cm/s}, s_2 = 300 \ \text{cm/s}. \]

Theoretical analysis shows that clear discrepancies between experimental curves and calculated curves occur at \( L_h = 950 \ \mu \)m for cases of surface recombination velocity \( s_1 = 10 \ \text{cm/s} \) (figure 6A) or for much higher values such as \( s_1 = 300 \ \text{cm/s} \) (figure 6B). These significant differences in the shapes of curves indicate the possibility of a fast estimate of contact quality at the injecting junction via observation of
the emergence and shift of the thermal radiation maximum at this junction. The further from the injecting contact this maximum occurs, the higher is the recombination velocity.

Since the diode thickness is much larger than the diffusion length, and the surface recombination velocities on polished and passivated surfaces perpendicular to the direction of observation are low, therefore the effective carrier lifetime in the base of the diode is only slightly affected by the surface recombination velocities at these perpendicular surfaces. Therefore the fitted values of carrier lifetime and surface velocities are close to their real values. Even if the surface recombination velocity on these polished and passivated surfaces is as much as 50 cm/s, the reduction of the bulk carrier lifetime is less than 20%.

**Figure 6.** Theoretical distribution of the carrier concentration along the base (the junction is on the left) calculated at (a) 180, (b) 380 and (c) 580 µs time delay after bias current is off. Parameters: \(s_1=10\) cm/s, \(s_2=300\) cm/s for figure 6A, and \(s_1=300\) cm/s, \(s_2=300\) cm/s for figure 6B.

### 4. Summary

The possibility of measuring surface recombination velocity at contacts and diffusion length in a germanium-based infrared radiation modulator from spatial and temporal distribution of infrared radiation of the heated structure was shown.

This new method enables fast control of contact quality via temporal observation of the spatial position of the maximum infrared radiation intensity relative to the injecting junction plane after forward bias applied to the junction is turned off.

### 5. References

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