Room-temperature resonant multiphotonic optical pumping induced by 10.6-μm laser radiation in reverse-biased n^+/p-type Si junctions

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Photoconduction induced by CO_2 laser pulses (10.6-μm wavelength) in reverse-biased silicon n^+/p-type junctions is experimentally studied. An interpretation on the basis of resonant multiphotonic excitation is discussed. We show that the quasiresonant intermediate states are spatially localized in the highly doped region near the surface of the n^+ zone.

I. INTRODUCTION

Carbon dioxide laser-induced voltages in reverse-biased commercial silicon photodiodes have been reported.[1] The time delay between the induced signal and the laser pulse was observed to be 40 ns. Both the photodiode signal and the laser pulse, appear to be highly correlated. It is assumed that an instantaneous uniform heating in the active region of the diode is the cause of the observed phenomenon. The thermally generated carriers will decrease the resistance of the diode and a change in the reverse current occurs.

In a recent Letter,[2] we described the observation and measurement of photovoltaic potentials induced by CO_2 transversely excited atmospheric-pressure (TEA) laser pulses in silicon photodiodes. The response consisted of a slight photon-drag effect at first, followed by a very long (up to 30-μs pulse width) and powerful pulseform. A net laser power threshold is observed.

The thermal model proposed in Ref. 1 is no longer useful in explaining a photovoltaic effect in nonbiased junctions. Furthermore, our wide pulseform cannot be correlated with the foreseeable laser-induced temperature evolution. Thus, to explain these observations, we have proposed a quasiresonant multistep multiphotonic process.

The aim of this paper is to obtain more complete information about this new phenomenon. Thus, we have performed photoconductive measurements in the same type of reverse-biased photodiodes excited by 10.6-μm laser pulses. On the other hand, the spatial localization of the interband levels interacting with radiation is not clear, as we discussed in Ref. 2. One experiment was also performed to clarify this point.

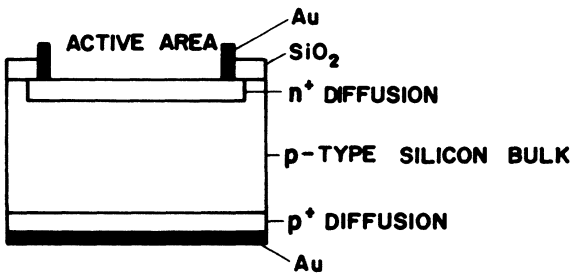

FIG. 1. Schematic diagram of the n^+/p structure.

II. PHOTODIODE CONSTRUCTION

The silicon photodiodes used were n^+/p structures (Fig. 1). The diodes were made on monocrystalline Si(111) and with 0.5 Ω cm resistivity (doping level $\simeq 10^{17}$ cm^{-3}). $POCl_3$ was used as the diffusion source for obtaining a heavily doped n^+ region in p silicon. The carrier gas was Ar and the injection gas was $Ar+O_2$; diffusion was carried out at 850 °C for 45 min. To obtain the p^+ rear layer, BN was used as the diffusion source. In this case, a carrier gas such as $Ar+O_2$ was employed. Diffusion was then carried out at 850 °C for 60 min. Thus the depth of the diffusion zone was about 0.45 μm. Ohmic contacts were made by evaporating a gold layer and afterwards annealing at 170 °C for 20 s. The active area was 12 mm^2.

III. EXPERIMENTAL SETUP

The radiation pulses were produced with an experimental CO_2 transversely excited atmospheric (TEA) pressure (TEA) laser, capable of producing 10.6-μm wavelength pulses with an energy of 7 J over an area of 2×2.5 cm^2. The time evolution of the radiation pulses was similar to that produced by a typical CO_2 TEA laser. It has a narrow gain switch pulse, 60 ns width, followed by a long tail (2 μs) of pumping which corresponds to the vibrational transfer. The maximum peak power was kept up to 10 MW/cm^2. Thus, the photodiodes were irradiated by nearly 10^{27} photons/cm^2 s. The power at the pulse tail was about 10% of the power at the pulse maximum. The laser energy falling on the photodiode could be regulated by means of a series of absorbers and was measured with a thermopile. The power was measured with a photon-drag detector having rise time <1 ns, and the pulses were recorded by a transient digitizer with a real time band-

width of 500 MHz. In order to avoid the stray field produced by radio frequency, the entire measurement system was placed inside a Faraday cage and the transmission lines were matched to 50 Ω. A 7-V photodiode reverse bias was used in the measurements. At higher voltages, spontaneous avalanche breakdown would probably occur.

IV. EXPERIMENTAL RESULTS

As was reported in the photovoltaic multiphotonic effect,[2] we initially had a slight photon-drag pulse followed by the photoconductive response. Although the photon drag pulse was synchronized to the light pulse, a time lag of about 40 ns (scarcely dependent on the light intensity) between the photoconductive response and the light pulse was observed, as in Ref. 1. The photoconductive response was present at a defined power threshold and saturation took place in a very short dynamic range (Fig. 2). Saturated pulse profiles are the same as those produced for pulsed visible light exciting an ordinary saturated photoconductive response. The fall times in the pulse profiles is the resistance-capacitance junction time.

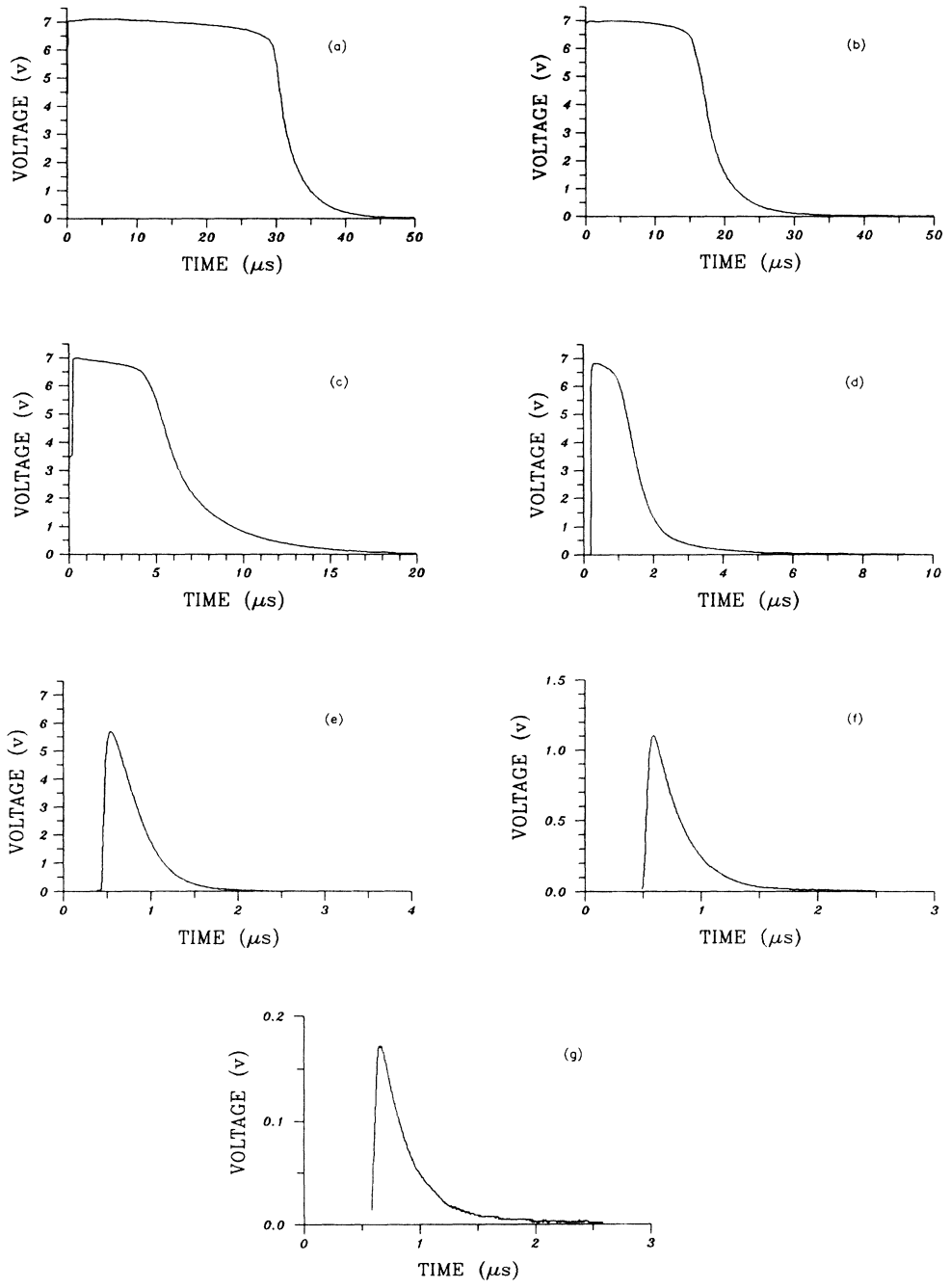

FIG. 2. Laser-induced photoconductive response for several values of the CO_2 laser intensity (gain switch peak). From (a) to (g), 10, 7, 4.8, 3.3, 2.3, 1.6, and 1 MW/cm^2.

Integrating the area below the response pulse profile, we calculated the number of carriers produced by the laser pulse. In Figs. 3(a) and 3(b) we show the carrier number against the number of incident photons, to get the effective quantum yield in the multiphotonic process.

As we pointed out in Ref. 2, multiphotonic absorption takes place through a sequence of jumps by a photon in quasiresonance, with intermediate states placed within the energy gap. These intermediate states may correspond to the known tail of the density of states, which are found within the energy gap in highly doped semiconductors.[3] However, another possibility suggests that the states might be present in the junction itself, as a consequence of the electric field found there.[4]

To elucidate between the two possibilities, a new experiment was performed. First of all we measured the p-type silicon substratum transmission with a result of 16%. The n^+/p structure transmission was also measured. The transmission in this case was below 0.1%. This was the result expected because the doping level was higher than 10^{20} cm^{-3} on the surface, where diffusion to build up the n^+ region took place. Since the free-carrier cross section at 10.6 μm for silicon is 5.4×10^{-16} cm^{-2} (Ref. 1) the absorption depth is $l_p=(n\sigma)^{-1}=0.018$ μm for $n=10^{21}$ cm^{-3}. The depth of the diffusion zone is about 0.45 μm. Then if the light impinges over the n^+ zone, a very low quantity of light arrives at the junction. On the contrary, with rear illumination (laser radiation directly impinging on the p substratum) a high level of light is attained in the junction. An n^+/p structure, where the rear contact as well as the front one are ring shaped, was built. In this structure the junction may be rear illuminated. The measured responsivity of this structure was a little smaller in rear illumination.

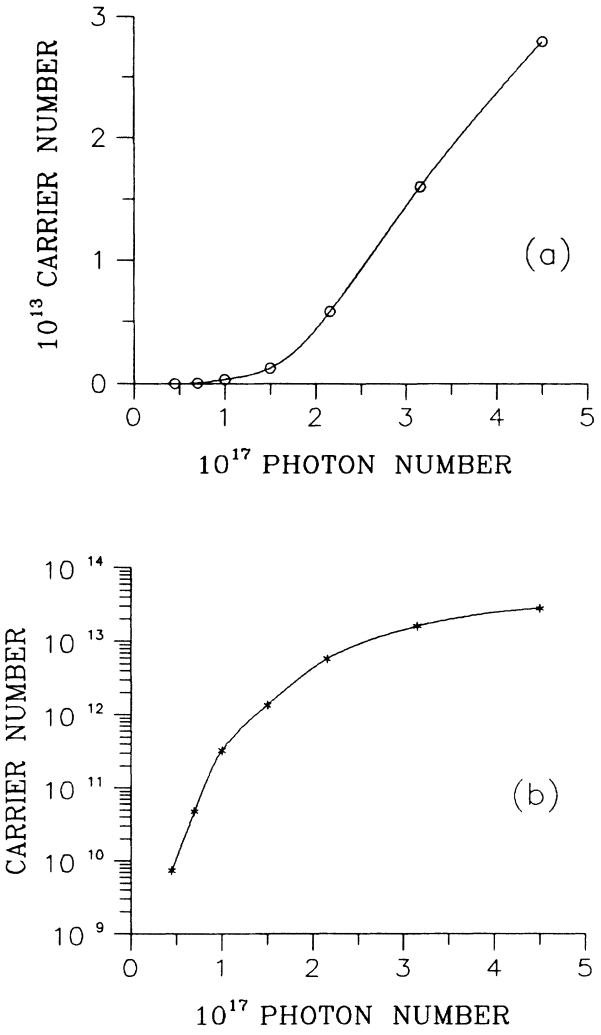

FIG. 3. Carrier number generated by the photoconductive response vs number of incident photons. (a) Linear scale; (b) logarithmic scale.

V. DISCUSSION

The photoconduction observation support the quasiresonant multistep multiphotonic excitation model (Fig. 4). In the n^+ region the photons are absorbed by free carriers in the conduction band, leaving holes in states near the bottom of this band. The following step is to excite electrons in impurity states inside the gap to the holes created in the prior step, leaving the corresponding empty impurity states. After ten steps (the energy gap of silicon is 1.11 eV and the photon energy is 0.117 eV) the first holes appear in the top of the valence band. The entire process requires the absorption of a threshold energy during a finite time. The nonlinear rate equations governing the process permit one to predict a nonlinear responsivity. The time delay, threshold intensity, and nonlinear behavior observed are consistent with the expectations. The existence of induced effect in nonbiased junctions[2] and the observed pulse profiles ruled out any thermal explanation as the proposed in Ref. 1. In fact, the expected time delay between the laser pulse and the thermal effect in the junction is

$$\Delta t=\frac{1}{a}\left[\frac{d}{2}\right]^2,$$

where a is the thermal diffusivity and d the junction depth. In Si in the temperature range 500–1700 K, a varies between 0.37–0.16 cm^2 s^{-1},[5] and in our structure $d=0.45$ μm, Δt being in the range 1.4–3 ns, which does

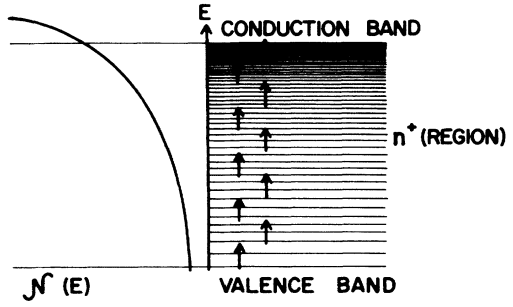

FIG. 4. Scheme of the quasiresonant multistep multiphotonic excitation through the impurity-state tail in the energy gap.

not agree with the observed experimental value $\Delta t \simeq 40$ ns. Furthermore, the Fourier number for the junction depth is

$$F = \frac{d}{2(a\Delta\tau)^{1/2}} ,$$

where $\Delta\tau$ is the laser pulse width. As $\Delta\tau \simeq 60$ ns we have $F \simeq 0.2$ and the thermal response should follow the laser pulse form which is not the observed situation.

The energy that reaches the junction is clearly higher in the rear than in the front illumination. Nevertheless, the obtained response is lower in the rear illumination. Thus, the main multiphotonic processes are not produced in the junction, but in the tail of intermediate states found within the energy gap in the highly doped surface layer. Other semiconductors are expected to produce the same effect described here. The responsivity is probably enhanced in junctions with lower energy gaps. On the other hand, the faint tail of intermediate impurity states is very efficiently detected by this effect. A theoretical approach to the described phenomena is not available as yet, but it will probably clarify some experimentally observed features.

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