Ultrafast Photoconductivity

Perhaps the biggest change in the THz landscape over the past 20 years or so has been the advent and widespread of ultrafast photoconductors for the generation of THz radiation. The most common generation technique, by far, is THz pulse generation using mode-locked lasers. Probably the second most common techniques is THz cw generation by the photomixing of two frequency-offset cw lasers. In both cases, the "ultrafast" photoconductors used must have an electron-hole recombination time $t < 1$ ps. While such photoconductors are rather commonplace today, their development required a challenging evolution in materials science along with advancements in mode-locked lasers, and THz printed-circuit and planar antennas technology.

No comprehensive discussion of the evolution of ultrafast photoconductors can ignore the success story of GaAs, which started with the incorporation or ion-implantation of select impurities, such as Cr, and culminated in high-quality material having photocarrier lifetime in the range of 10-to-100 ps. A lasting legacy of this impressive development is, in fact, the Cr-doped semi-insulating (SI) substrate used universally for epitaxial growth of all types. For ultrafast applications, SI GaAs was superseded in the early 1990s by low-temperature-grown (LTG) GaAs. The technological breakthrough of LTG GaAs and, indeed, the *mantra* for this development was "defect engineering." A key discovery was that low-temperature growth by MBE at around 200°C followed by an anneal in the range 500-600°C would create, in addition to substitutional (e.g., antisite) defects, a significant concentration of As-rich *precipitates*.[1,2] The *precipitates* were associated with a large density of energy levels very near the center of the GaAs band gap where they tend to accelerate the bipolar recombination, leading to deep-subpicosecond photocarrier recombination time under cross-gap illumination just above the GaAs band-edge.[3] A drawback of the LTG-GaAs material was the unavoidable creation of more shallow levels - electron and, particularly, hole traps. If influential in the recombination kinetics, such traps can impact ionize in strong bias electric fields, creating a significant increase in the lifetime.[4]

In the late 1990s a new approach to ultrafast GaAs was pioneered by the group of A.C. Gossard which entailed the incorporation of Er during normal growth of GaAs.

Under the right conditions, the Er was shown to form single-crystal ErAs *nanoparticles* embedded in nearly-defect-free GaAs. In effect, the As-*precipitates* in LTG GaAs had been created without all the associated defects. Almost immediately, the ErAs:GaAs material demonstrated deep-subpicosecond photocarrier recombination time.[5] More recently this has lead to the development and application of record-breaking THz photomixers.[6]

The parallel story for InGaAs started in the early 1990s, propelled largely by the advent of erbium-doped fiber amplifiers (EDFAs) and their associated components. The development effort is summarized by the published results listed in Table I. Low-temperature growth was attempted early on and led to the achievement of ~1.0 ps lifetime at 1.55 μm in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells[7,8] and interesting ultrafast nonlinear absorption effects.[9] Subpicosecond response was not reported and slowly became somewhat of a "holy grail" of 1.55-micron ultrafast field. So by the *new millenium* researchers were pursuing techniques other than low-temperature growth, the first successful one being old-fashioned but very careful ion implantation. The first subpicosecond results were achieved by Au+ and H+ (i.e., proton) implantation of $In_{0.53}Ga_{0.47}As$ epitaxial layers.[10] Shortly thereafter, lifetime down to 300 fs was reported in Fe^{+}-implanted material.[11]

Naturally, Er incorporation was pursued in parallel with the ion-implantation studies and, along with Be doping for electron compensation, was able to create high-quality material with embedded ErAs nanoparticles.[12] The first material had ErAs

Table I. Summary of published results for ultrafast photoconductors at λ = 1.55 μm.

Material	Measured Lifetime at or near λ = 1.55 μm	Reference
LTG, Be-doped InGaAs/InAlAs quantum wells	1.5 ps	[8]
LTG, Be-doped InGaAs/InAlAs quantum wells	Subpicosecond nonlinear absorption recovery	[9]
Au and H-implanted InGaAs layers	< 1 ps	[10]
Fe-doped InGaAs epilayers annealed between 500-600°C	300 fs	[11]
Be-doped 40-nm-period ErAs-InGaAs epilayer	~1 ps	[14]
δ-doped-Be, ErAs-InGaAs epilayer	< 300 fs	[16]

nanoparticle layers separated by 40 nm and displayed lifetime just 1 ps at ~800 nm pump wavelength;[13] however, the lifetime in this material could only reach ~1.0 ps at 1.55 micron.[14] And even though the materials was Be doped to reduce the background free electron concentration, the "dark" resistivity of the material was prohibitively low for ultrafast photoconductive applications.[15] A heroic investigation involving more closely spaced ErAs layers (5 nm) and Be *modulation-* and *delta-doping* subsequently led to a significant reduction in lifetime, the shortest reported value being just under 300 fs.[16] In fact, it is the latter results that motivated the next section of the present paper on the extraction of lifetimes at 1.55 micron wavelength when they are in this deep-subpicosecond regime.

Mode-Locked Lasers and Photoconductive Response

One of the greatest inventions in quantum electronics has been the mode-locked laser. The time-dependent pulses from mode-locked lasers are often represented by the time-dependent power, $P_{pump}(t) = P_0 \,\mathrm{sech}^2[a(t-t_0)]$. A good approximation to this function and a form much easier to evaluate by signal-processing techniques is the Gaussian,

$$P_{pump}(t) = P_{0,pump}\exp[-b(t-t_0)^2]. \qquad (1)$$

In either case, if derived from mode-locked lasers having low repetition rates (f_{rep} ~100 MHz) compared to the inverse pulse width, the average power is to an excellent approximation $P_{ave} \approx f_{rep} \cdot U_{pulse}$ where $U_{pulse} = \int_{-\infty}^{\infty} P_{pump}(t)dt$. Representative curves for these two functions are plotted in Fig. 1 for single pulses having the same U_{pulse}. Note that since $U_{pulse} = 2P_{0,pump}/a$ for the sech^2 function and $U_{pulse} = P_{0,pump}(\pi/b)^{1/2}$ for the Gaussian,[17] the two pulses in Fig. 1 have the relationship $b=\pi a^2/4$. Separate analysis shows that the full-width at half-maximum is $FWHM_S = 1.762/a$ for the sech^2 function and $FWHM_G = 1.665/(b)^{1/2}$ for the Gaussian. Hence for the same f_{rep} and the same pulse energy, the two pulse forms satisfy $FWHM_S = 0.881U_{pulse}/P_{0,pump} = 0.881\,(\pi/b)^{1/2} = 0.938$ $FWHM_G$. In other words, the sech^2 pulse form provides a 6% shorter pulse width, all other factors being equal.

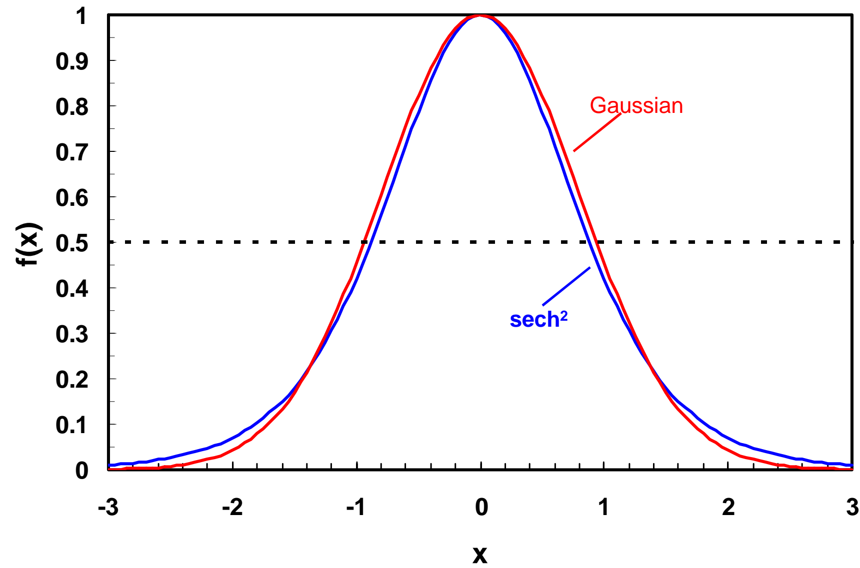

Fig. 1. Comparison of Gaussian and sech^2 functional forms of the instantaneous power from a single mode-locked laser pulse. The pulse energy (integral from x = -∞ to ∞) is the same for both curves

The dynamics of the excess free-carrier density is a critical part of the analysis and also a subtle issue in ultrafast photoconductors because it is a sensitive function of the photocarrier-recombination mechanisms. The assumption is made here that the recombination is *bimolecular*, meaning that excess electrons and holes annihilate in pairs and the excess density is governed by a rate equation

$$\frac{d\rho}{dt} + \frac{\rho}{\tau} = g(t)\,. \qquad (2)$$

where τ is the lifetime. The generation rate g(t) is the number of electron-hole pairs created per unit volume per unit time, and is assumed here to depend on the pump intensity as $g(t') = \alpha_0 I(t')/h\nu \approx \alpha_0 B P_{pump}(t')/h\nu$ where B is a constant of dimension m^{-2}.

The solution to (2) including both the homogeneous and inhomogeneous (i.e., particular) solutions is expressed elegantly from signal-processing theory using the impulse response function, $G(t,t') = \exp[-(t-t')/\tau]$. Hence,

$$\rho(t) \equiv \int_{-\infty}^{t} G(t,t')g(t')dt' = \int_{-\infty}^{t} \exp[-(t-t')/\tau]g(t')dt' \qquad (3)$$

This solution obeys causality and it is analytic for a Gaussian pump pulse, here assumed to be centered at t' = 0. Assuming the Gaussian pulse form of (1) centered at $t_0 = 0$, one gets

$$\rho(t) = \int_{-\infty}^{t} \exp[-(t-t')/\tau] \cdot \alpha_0 B P_{0,pump} \exp[-b(t')^2]/(h\nu) \cdot dt'$$

$$= \frac{\alpha_0 B P_{o,pump}}{h\nu} \exp(-t/\tau) \left\{ \frac{\sqrt{\pi} \cdot \exp[1/(4b\tau^2)]}{2\sqrt{b}} \left[erf(\sqrt{b} \cdot t - \frac{1}{2\sqrt{b} \cdot \tau}) + 1 \right] \right\} \quad (4)$$

where erf is the *error function* with integral representation $erf(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt$,

perhaps the most widely used special function in probability theory and statistics, and now easily computed as a library function in practically any spreadsheet tool.

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[15] Unfortunately, not all ultrafast photoconductive studies report the "dark" electrical resistivity – a very important quantity since any photoconductive device requires large electrical bias, and high dark conductivity leads to device burn-out long before useful ultrafast performance is obtained.

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[17] Note: $\int_{-\infty}^{\infty} \sec h^2(ax)dx = (1/a)\tanh ax\Big|_{-\infty}^{\infty}$ = 2/a, and for the Gaussian $\int_{-\infty}^{\infty} \exp(-bx^2)dx = \sqrt{\pi/b}$.