Brief, Incomplete Summary of Some Literature on Ionization

Regimes of Photo Ionization

There are two limiting regimes for ionization in strong optical fields. From reference [1]. The ratio γ of the tunneling time (i.e. the width of the barrier divided by the electron velocity) to the optical period is known as the adiabaticity or Keldysh parameter and is generally used to separate the two regimes,

$$\gamma = \left(\frac{IP}{2U_p} \right)^{1/2} \tag{1}$$

where IP is the atom ionization potential and $U_p = E^2 \big/ \left(4\omega^2\right)$ is the mean quiver energy in the laser electric field.* In the low frequency limit ($\gamma \ll 1$) ***tunnel ionization*** is a good description of the transition dynamics. This is typical of rare gases ionized by a CO_2 laser, in which case the electron tunnels out in a time less than half the field period. In the other limit ($\gamma \gg 1$), the ***multiphoton*** character is evident in the photoelectron spectra as a structure repeated with the photon energy period (above ionization threshold) and whose rate scales as I^N, where I is the intensity and N is the number of absorbed photons.

From reference [2]. Above a certain electric field the electron is able to escape even classically from the atomic nucleus, i.e. without tunneling through the barrier formed by the Coulomb potential and the external electric (laser) field. This regime is called ***barrier-suppression ionization***.

Bruhwiler *et al* [3] calculate the tunnel ionization threshold for Li to be ~ 4 GeV/m with 100% ionization at 6 GeV/m. They calculate that the critical field requiring a barrier suppression model is 18.7 GeV/m.

Breakdown in Dielectrics and Laser Pulse Length Dependence

Simanovskii *et al* [4] study the breakdown of dielectric materials. In their introduction they discuss the pulse length dependence of the ionization processes that provide the seed electrons that initiate avalanche ionization and breakdown. Tien *et al* [5] discuss dependences of multiphoton and tunnel ionization on pulse length and wavelength. From reference [5]. When the pulse length becomes shorter and multiphoton ionization becomes more important, shorter wavelengths have higher electron yields than longer wavelengths. When the pulse duration is extremely short, where the electric field is extremely high, tunnel ionization should be considered instead of multiphoton ionization. In the tunnel ionization regime, the dependence of damage threshold on wavelength becomes weak again.

Reference [4] measures the wavelength dependence of breakdown in different dielectrics for 1 psec laser pulses and for λ in the range 400 nm to 8 μm. They explain their results in terms of tunnel ionization at long λ and multiphoton ionization at short λ.

ADK Ionization Rate

There are a number of theories of ionization. References to them are given in [2]. Bruhwiler *et al* [3] use the ADK (Ammosov, Delone and Krainov) model [6]. This is the ionization model used in OOPIC and in the E164 field ionization studies.[7]. Bruhwiler *et al*

* This expression for U_p is from reference [2], which uses atomic units.

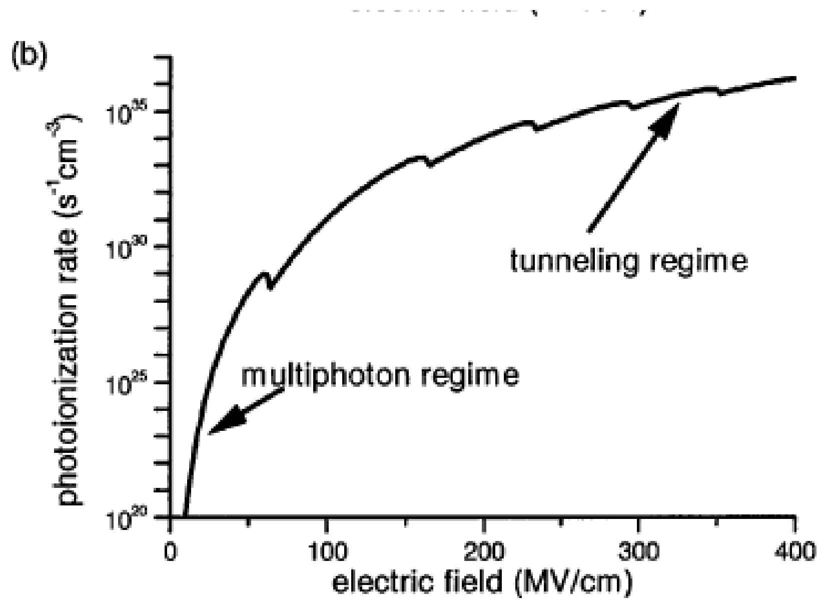


Figure 2b from reference [5] showing typical a photoionization rate in solids as predicted by Keldysh's model [8].

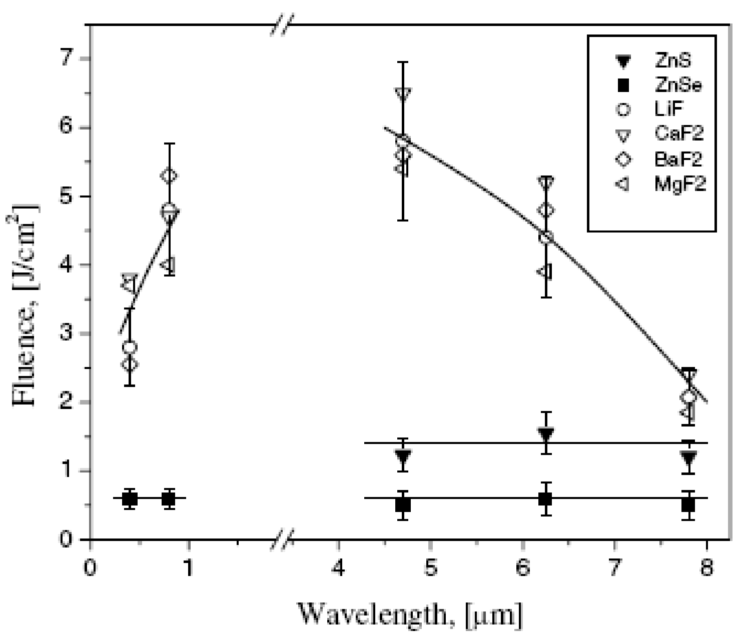


Figure 3 from reference [4] showing the wavelength dependence of the breakdown threshold for wide- and narrow-gap material.

gives an expression for the quasistatic rate – the rate assuming that the external electric field changes slowly compared to the time scales of interest. This is in contrast to a time-averaged rate that would be used for a rapidly varying electric field where the expression for the envelope is used. The justification for using the quasistatic result in OOPIC is that the time variation of the electric field is fully resolved.

Beam Field Ionization

In the case of field ionization caused by an electron beam the Keldysh parameter will be the ratio of the tunneling time to the electron pulse length. It is small due to the long length of the beam pulse (as compared to an optical period). Therefore, beam field ionization is in the tunnel ionization regime, as opposed to the multiphoton ionization regime.

"Ionization in the Field of a Strong Electromagnetic Wave" [8]

This paper by L. V. Keldysh contains the theory that is the basis for much of the discussion about ionization. The first part of the abstract reads "Expressions are obtained for the probability of ionization of atoms and solid bodies in the field of a strong electromagnetic wave whose frequency is lower than the ionization potential. In the limiting case of low frequencies these expressions change into the well known formulas for the probability of tunnel auto-ionization; at high frequencies they describe processes in which several photons are absorbed simultaneously." In the first part of the paper a general expression for the ionization of individual atoms is derived.

The second part of the paper deals with ionization in a crystal where an electron makes a transition from the valence to the conduction band, i.e. to the creation of an electron-hole pair. The Keldysh parameter for a dielectric differs from that for an atom. It is [8]

$$\gamma = \frac{\omega\sqrt{m\Delta}}{eE} \tag{2}$$

In the limit of low frequencies and strong fields ($\gamma \ll 1$) the tunnel ionization rate, the time rate of change of the conduction electron density (ρ), is (eq. (40) of [8])

$$\frac{d\rho}{dt} = w = \frac{2}{9\pi^2}\frac{\Delta}{\hbar}\left(\frac{m\Delta}{\hbar^2}\right)^{3/2}\left(\frac{e\hbar E}{m^{1/2}\Delta^{3/2}}\right)^{5/2} \times \exp\left(-\frac{\pi}{2}\frac{m^{1/2}\Delta^{3/2}}{e\hbar E}\left(1-\frac{1}{8}\frac{m\omega^2\Delta}{e^2E^2}\right)\right) \tag{3}$$

where the electric field is $E\cos(\omega t)$, Δ is the bandgap between the valence and conduction bands, and *m* is the reduced mass of the electron and hole

$$\frac{1}{m} = \frac{1}{m_e} + \frac{1}{m_h} \tag{4}$$

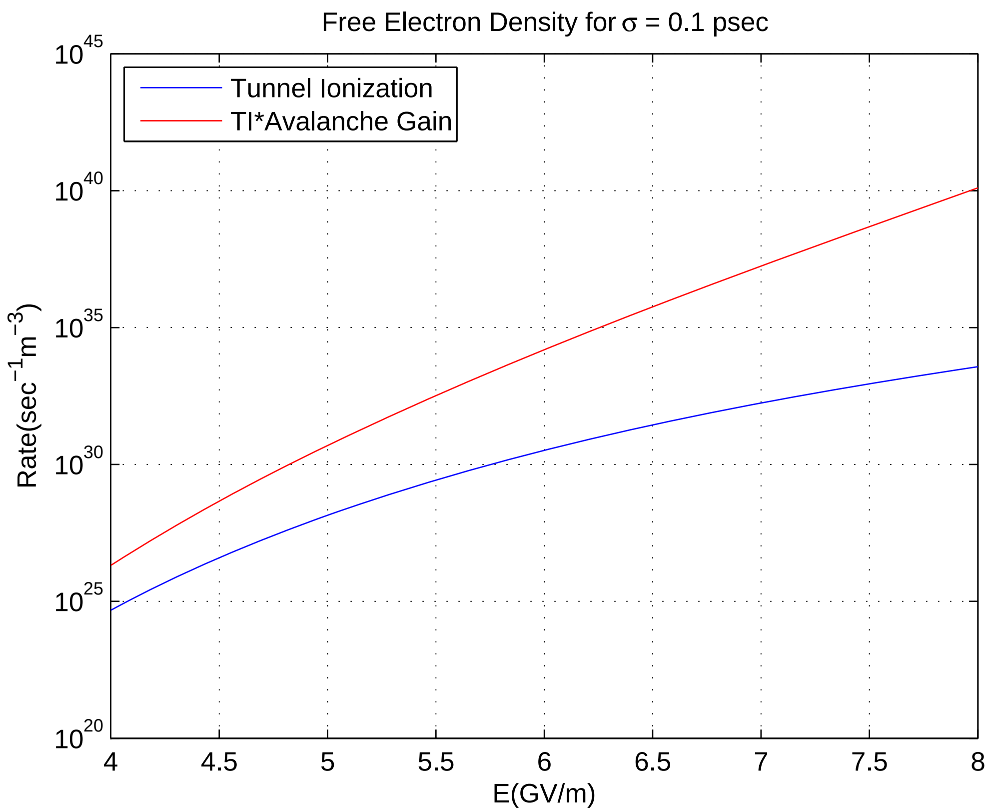
The rate *w* has units $\sec^{-1}m^{-3}$ as expected because it is the time rate of change of a density.

Dielectric Damage

The model for dielectric damage is 1) the initiation of damage through the production of free electrons, 2) this is followed by an avalanche that increases the number of free electrons until a critical density is reached. Stuart *et al* [9] state that the critical density for damage is in the range 10^{25} to 10^{27} electrons/m^3. An estimate of the amplification due to the avalanche is in eq. (23) of ref. [9]. To convert this equation into one that can be used for a beam induced breakdown of a dielectric, assume the electric field pulse from the beam is Gaussian

$$E = E_{peak}\exp\left(-\frac{t^2}{2\sigma^2}\right) \tag{5}$$

The Gaussian σ of the electric field pulse and the FWHM for the laser intensity pulse are related by $\sigma = \tau/\sqrt{4\ln 2}$. Approximating $I_0 = E_{peak}^2/Z_0$ gives an avalanche amplification of



Free electron density for fused silica

$$Gain = \exp\left(\frac{\sqrt{\pi}}{2}\frac{\alpha E_{peak}^2 \sigma}{Z_0}\right) = \exp\left(2.35 E_{peak}^2 \sigma\right) \tag{6}$$

where $\alpha = 10^{-3}\, m^2/J$ was used and E_{peak} is in GV/m and σ is in psec in the right-hand expression.

Use Δ = 9 eV and $m = 0.5\, m_e$ for fused silica [10]*. The electron density calculated from eq. (3) with and without amplification due to the subsequent avalanche for λ = 10 μm (not a sensitive parameter in the tunnel ionization regime) and σ = 0.1 psec is given in the figure above. The rate for dielectric breakdown would be in the range 10^{38} to 10^{40} sec^{-1}m^{-3} for a 0.1 psec pulse implying a breakdown threshold of ~7.5 GeV/m. This result is sensitive to parameters (for example the assumed value for critical density and the reduced mass). The exponential nature of the result is much more significant than the specific numbers. For example there are ~6 orders of magnitude in the rate and free electron density as the critical field goes from 6 to 8 GeV/m.

* Results are sensitive to the value assumed for m. Ref. [10] assumes $m = 0.5\, m_e$ while ref. [9] assumes $m = m_e$.

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