A physical model on the initiation of atmospheric-pressure glow discharges*

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A model on the preionization requirements for initiating a volume-stabilized glow discharge is proposed. The basic requirement of the model is that the preionized electron density be large enough to cause appreciable spatial overlap of the primary avalanches and consequent smoothing of space-charge field gradients at the stage when streamer formation would otherwise occur. A minimum required preionization electron density of $-10^4$ cm$^{-3}$ is predicted for a typical CO$_2$ TEA laser discharge and is consistent with experimental observations.

Preionization of laser gases by uv photoionization or by the double-discharge technique has proven to be an effective means of initiating volume-stabilized glow discharges between shaped electrodes at gas pressures greater than 1 atm.$^{1-4}$ While application of this technique has become common, particularly to the CO$_2$ laser system, and the photoionization processes specific to the uv preionization technique used on the CO$_2$ lasers have recently been clarified,$^1,5-9$ the basic physics of the conditioning mechanism itself has yet to be elucidated. It is the purpose of this paper to suggest a simple physical model as descriptive of the basic preconditioning requirement for initiating a volume-stabilized glow discharge. Some experimental observations supportive of the model are also referred to.

At moderate to high gas pressures, two types of breakdown mechanisms can occur. One is called Townsend or Paschen breakdown, wherein simple Townsend avalanches build up in a space-charge-free field to the point where secondary emission from the cathode provides sufficient feedback of electrons to maintain the discharge. This leads to the well-known Paschen breakdown law$^{10}$:

$$p_d = \frac{1}{\alpha/P} \ln \left(1 + \frac{1}{\gamma}\right),$$

(1)

where $P$ is the pressure, $d$ is the electrode gap, $\alpha$ is the Townsend first ionization coefficient for the gas, and $\gamma$ is the Townsend second ionization coefficient for the cathode surface.

The other breakdown mechanism is termed streamer breakdown and it occurs when $p_d$ becomes large enough to permit the space-charge field of a single avalanche to become comparable to the applied field. In this case secondary avalanches initiated by photoionization will tend to converge towards the primary [Fig. 1(a)] avalanche leading rapidly to the development of a highly conducting filamentary channel which bridges the gap [Fig. 1(b)] and quickly brings the discharge to self-sustaining conditions usually in the form of a spark.

The streamer breakdown condition is stated simply as the equality of the local avalanche space-charge field to the applied field. This condition is commonly known as Raether's breakdown criterion and can be written (for air, in mks units) as$^{10}$

$$(\alpha/P)p_d = 20 + \ln d.$$

(2)

In situations where one can suppress arc formation through the use of ballast resistors or other current-limiting elements in the external circuit, it is clearly unimportant which breakdown mechanism is operative. Unfortunately, it is not possible to achieve this type of discrimination for the type of volume-stabilized atmospheric-pressure discharges under consideration here. The breakdown mechanism is therefore decisive as to which initial self-sustained discharge mode will occur in these systems. The streamer breakdown criterion given by Eq. (2) is easily satisfied for a typical TEA laser discharge. Clearly such a breakdown mechanism, if allowed to progress in the normal manner described above, will favor an arc mode rather than the desired glow mode initiation of the discharge. The glow-to-arc transition instability, which in any case usually terminates the glow phase, is not considered here, although the occurrence of the instability might in some cases be related to the breakdown conditions.

![Diagram of streamer breakdown](image)

**FIG. 1.** Streamer breakdown initiated by a signal primary avalanche: (a) Initial, (b) final charge distributions.
FIG. 2. Preionized breakdown initiated by multiple primary avalanches: (a) Initial, (b) final charge distributions.

How does preionization alter the situation so far described? To best answer this question, it is first necessary to briefly review the derivation of the streamer breakdown criterion given by Eq. (2).

The lateral extent (perpendicular to the field direction) of an individual avalanche is usually assumed due to diffusion, although electrostatic repulsion may be necessary to briefly review the derivation of the streamer field. One calculates the space-charge field \( \mathcal{E} \) of the avalanche by assuming that all of the electrons in the avalanche, \( N_e \), are concentrated in the head of the avalanche which is assumed spherical with radius \( r \). One writes, therefore,

\[
\mathcal{E} = \frac{e}{4\pi \varepsilon_0} \cdot \frac{N_e}{r^2},
\]

(4)

where \( e \) is the electron charge, \( \varepsilon_0 \) is the free-space permittivity, and \( N_e \) is given by the Townsend avalanche condition:

\[
N_e = \exp(\alpha z).
\]

(5)

Equating the space-charge field at the surface of the avalanche head to the applied field \( \mathcal{E}_0 \) by using Eqs. (3)–(5) gives a formula for the critical distance \( z_{\text{crit}} \), which an individual avalanche must propagate to initiate streamer breakdown:

\[
\alpha z_{\text{crit}} = \ln(4\pi e \mathcal{E}_0 \mathcal{E}^5/e) + \ln z_{\text{crit}}.
\]

(6)

The first term in the right-hand side is fairly insensitive to the gas parameters and is about 20 in mks units for typical breakdown conditions. \(^{10,11}\) Equating \( z_{\text{crit}} \) to the gap spacing \( d \) gives Naether's criterion, Eq. (2).

Now the above criterion for streamer formation contains no dependence on the initial (preionized) electron density. What is also important for streamer formation but is not explicitly stated in Eq. (6) is that the space-charge field has an appreciable local gradient since it is this feature which causes the ionization to become filamentary. In the case where the space-charge field is due to a single primary avalanche as assumed for the derivation of Eq. (6), such a local gradient clearly exists. However, as the density of primary avalanches is increased, the field gradient associated with the avalanche space charge will be smoothed out. At a high enough avalanche density the space-charge fields can be expected to become sufficiently uniform to eliminate the tendency of the secondary avalanches to converge towards a single primary avalanche [Fig. 2(a)]. Let \( n_0 \) represent the density of primary avalanches (preionization electron density). The ratio \( (n_0)^{1/3}/r \) can then be taken as a measure of the smoothness of the avalanche space-charge fields, where \( r \) is the lateral extent of the avalanche [Eq. (1)] and \( (n_0)^{1/3} \) is the average lateral separation of the avalanches. It is reasonable to assume that filamentary streamer formation will be suppressed in favor of a more uniform space-charge-controlled ionization stage which can initiate a uniform glow discharge when the value of this ratio becomes less than or comparable to unity at the critical stage when space-charge fields become comparable to the applied field [Fig. 2(b)]. This condition can be written, using Eq. (3), as

\[
(n_0)^{1/3} \leq (\mathcal{C}_e z_{\text{crit}})^{1/2},
\]

(7)

with \( z_{\text{crit}} \) given by Eq. (16).

Typical parameters for CO\(_2\) TEA breakdown conditions are \( \mathcal{C} \approx 10^{-3} \) cm, \( \mathcal{C} \approx 10 \) cm\(^{-1} \). For these values, Eqs. (7) and (6) require, for glow mode initiation,

\[
n_0 \geq 10^6 \text{ cm}^3.
\]

Note that to first order, \( n_0 \) varies with the cube of the pressure (for fixed \( \mathcal{E}/p \)).

The above threshold preionization density is consistent, in order of magnitude, with experimental observations. Preionization levels employed in spark-preionized CO\(_2\) laser systems have been measured using microwave interferometry\(^6\) and charge collector probes.\(^5,6\) The portion of the uv emission spectrum responsible for photoionization in these systems was found to be in the 1200–1300-Å transmission window of the CO\(_2\) molecule.\(^5,6\) The observed photoionization electron density was found to be consistent with the presence of an impurity in the bottled gases at a concentration level on the order of 1 ppm with a photoionization cross section at 1200–1300 Å of on the order of \( 10^{-18} \) cm\(^2\).\(^5,6\) By aperturing the uv flux from resistor-ballasted spark uv sources, a rough estimate of the threshold 1200–1300-Å uv illumination of the discharge gap for glow mode conditioning has been found at this laboratory to be \( 10^{-3} \) W/cm\(^2\) for a 1 \( \mu s \) duration corresponding to a preionized electron density on the order of \( 10^6 \) cm\(^{-3}\)\(^5\). Other spark–preionized CO\(_2\) laser systems have been...
reported to operate at a preionization electron density level of $\sim 10^9 \text{ cm}^{-3}$.\textsuperscript{6}

Implicit in the above model for glow mode conditioning is the assumption that the preionized electron density is uniform throughout the discharge volume. In this case the threshold condition given by Eq. (7) would appear to be a sufficient condition for arbitrarily large discharge volumes. For the more general case of nonuniform preionization, for which conditioning by cathode photoelectric emission is a special case, the criterion given by the threshold condition given by Eq. (7) may not be a sufficient condition. Establishing only a local preionization density near the cathode in a relatively large discharge gap, for example, does not assure suppression of streamer formation ahead of the assessment of the threshold conditions for this more volumes. For the more general case must involve a comparison of the growth rates of both the uniform and filamentary phases of the space-charge-controlled ionization. Such an analysis is not attempted here but is the subject of current investigations.

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Scanning electron micrographs of self-quenched breakdown regions in Al-SiO$_2$-(100)Si structures*

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SEM photographs of regions of breakdown produced in vacuum ($10^{-3}$ Torr) are exhibited for four basic Al-SiO$_2$-(100)Si configurations: $p$ substrate, field plate + and field plate -, and $n$ substrate, field plate + and field plate -. With $p$-Si and field plate +, the geometry of the breakdown region reflects the anisotropic conductivity of hot electrons in Si along the (100) plane of the substrate wafer. Some properties of the breakdown correlate with the nature of the substrate surface channel (inversion versus accumulation); other properties correlate with the field-plate polarity.

Scanning electron microscope (SEM) observations of self-quenched breakdown (SQBD)\textsuperscript{1} regions in MOS capacitor structures have previously been reported in both the secondary-electron and beam-induced-current modes.\textsuperscript{2} Here detailed SEM photographs of individual SQBD regions in Al-SiO$_2$-(100)Si structures are presented in order to exhibit the characteristic topographic structure of the breakdown in four basic configurations: $p$-Si substrate, field plate + and field plate -, and $n$-Si substrate, field plate + and field plate -. A particularly striking result is the crystallographic orientation of the breakdown region in one of the four configurations: $p$-Si substrate in inversion (field plate +).

Both $p$ and $n$ substrates were (100) oriented and of resistivity $\sim 1 \Omega \text{ cm}$. The SiO$_2$ was thermally grown to a thickness $\approx 2500 \AA$. The Al field plates, of diameter 1.3 mm, were evaporated to a thickness $\approx 1000 \AA$. The breakdown events, studied under constant applied voltage conditions, had their onset at nominal (average) fields of $7-8 \times 10^7 \text{ V/cm}$. Following the onset of a breakdown event, the time decay, then recovery, of the capacitor voltage was monitored on a high-speed oscillo-