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Atomic hydrogen cleaning of InP(100): electron yield and surface morphology of negative electron affinity activated surfaces

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Abstract

Atomic hydrogen cleaning of the InP(100) surface has been investigated using quantitative reflection high-energy electron diffraction. The quantum efficiency of the surface when activated to negative electron affinity has been correlated with surface morphology. The electron diffraction patterns showed that hydrogen cleaning is effective in removing hydrocarbons and oxides, leaving a clean, ordered, and (2×4)-reconstructed surface. After activation to negative electron affinity, a quantum efficiency of ~ 6% was produced. Secondary electron emission from the hydrogen-cleaned InP(100)-(2×4) surface was measured and correlated to the quantum efficiency. The morphology of the vicinal InP(100) surface was investigated using electron diffraction. The average terrace width and average string length were measured from the (00) specular beam profile at the out-of-phase condition. The average string length at step edges was found to increase with hydrogen cleaning time, although there was some reduction in the average terrace width with hydrogen cleaning time. The surface quality was improved with hydrogen cleaning as indicated from the increased (00) spot intensity-to-background ratio at the out-of-phase condition, and improved quantum efficiency after activation to negative electron affinity.

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PACS numbers: 61.14.-x, 79.20.-m, 79.60.-i, , 81.65.-b

I- INTRODUCTION

Indium phosphide is a material of considerable importance in the area of developing electronic and optoelectronic devices. InP-based high electron mobility transistors (HEMTs) are attractive for low noise, high power, and high speed applications.[1] Preparation of high quality InP surfaces is an important step prior to epitaxial growth. Surface defects lead to degradation in the growth of heterostructures. Efficient cleaning at low substrate temperatures is becoming important to eliminate the interface carrier depletion region and minimize defect-induced surface states.

InP is used for negative electron affinity (NEA) device fabrication, and consequently preparation of a clean surface is required in order to reduce the density of surface states. Surface contamination produces lower quantum efficiency (QE) photocathodes. The main contaminants observed on InP surfaces are carbon and oxygen.[2] Chemical cleaning alone does not provide a carbon free surface.[3] Native oxides are desorbed by heating to ~ 500–530 ^{o}C, a temperature much higher than InP congruent temperature (~ 400 ^{o}C) at which the phosphor atoms desorb preferentially leaving an indium-rich rough surface with poor electronic quality.[4,5] Adsorbed carbon is strongly bonded to III-V surfaces and remains on the surface even after annealing under phosphine overpressure at high temperature.[6]

Considerable interest has been devoted to methods of producing clean InP surfaces and avoiding phosphorus loss that leads to creation of electronic defects. Surface cleaning of InP and GaAs using atomic hydrogen has been studied.[2, 5, 7] Atomic hydrogen cleaning is used for substrate preparation before epitaxial growth[7,8] or activation to NEA.[9] The main advantages of this technique are low cleaning temperature and avoiding degradation to the surface electronic properties, which occurs in hydrogen plasma cleaning due to the presence of energetic ions (up to ~ 100 eV) causing surface damage. The interaction of atomic hydrogen with semiconductor surfaces has been the subject of many studies.[10-12] Hydrogen cleaning of III-V semiconductors has been reported using rf discharge,[7] electron cyclotron resonance discharge,[13] and a hydrogen thermal cracking source.[2] Thermal sources produce hydrogen radicals with kinetic energies typically less than 1 eV,[14] and, thus, atomic hydrogen interaction is limited to the surface top layer. Exposure to atomic hydrogen removes surface contaminants and blocks the electrical activity of dangling bonds.[4] Atomic hydrogen reacts with the stable In oxide, In_2O_3, and lowers the cleaning temperature by producing a more volatile In oxide, In_2O.[2] Auger analysis of InP surfaces shows complete removal of carbon and oxygen after hydrogen cleaning.[2] The dissociative adsorption of NH_3 and SiH_4 on InP surfaces has been studied.[15,16] It was shown that it takes much longer irradiation time to clean the InP surface than it takes for cleaning the GaAs surface.[5] For InP, atomic hydrogen cleaning can be accomplished at a surface temperature ~ 350-400 ^{o}C.[9] This process is limited by the removal of hydrocarbons, which persist at high temperatures, and the relatively high temperature needed to remove indium phosphate, $In(PO_3)_3$.[5]

Reflection high-energy electron diffraction (RHEED) is a useful *in situ* technique to study the surface morphology. Surface processes such as thin film growth, phase transformation, and changes in surface morphology can be investigated by quantitative RHEED.[17] A vicinal surface is slightly inclined to a low free energy, low-index surface.[18,19] When the electron beam is incident down the staircase, the RHEED pattern is modified by the step structure and a splitting streak is obtained at the out-of-phase condition. In this case, the RHEED patterns is most sensitive to surface defects. From the split peak spacing and their widths at the out-of-phase condition, surface terrace width and string length of the vicinal surface can be measured.[17] The split peak spacing depends on the incident electron beam angle relative to the stair case direction. RHEED was previously used to study surface cleaning of hydrogen-plasma treated GaAs and Si surfaces.[20]

A surface with NEA is obtained when the vacuum level is lowered below the bulk conduction band minimum at the surface, thus, electrons excited to the conduction band minimum can be emitted from the surface. The escape depth in this case is not limited by the mean-free path of the hot electrons, which is on the order of 10 nm, but by the diffusion length of the electrons thermalized to the conduction band minimum, which is on the order of several μm.[21] Achieving NEA requires the combination of electron affinity lowering and downward band bending,[22] and thus p-type doping is favored. NEA surfaces are utilized in a number of important applications, such as secondary electron emitters and cold-cathode emitters. The high secondary emission results from the NEA at the surface of the sample along with a long escape depth for the internal secondaries.[23] Hydrocarbons and oxides present on the surface causes the presence of a surface energy barrier. For GaAs, air-exposed surfaces are known to contain a high density of surface states which pin the surface Fermi level at midgap.[24] For a clean surface when coated with adatoms such as cesium and oxygen, NEA can be attained. Under these conditions, low-energy electrons activated to the bottom of the conduction band can escape into the vacuum through the surface.

We prepared NEA InP(100) surface as described previously.[9] In the present work, the effect of atomic hydrogen cleaning on surface morphology and electron emission performance of the surface is studied. RHEED is used to monitor the development of the surface with atomic hydrogen cleaning time. The secondary electron emission from the hydrogen-cleaned InP(100)-(2×4) surface is studied. The QE and secondary-yield are shown to increase with hydrogen cleaning. We have previously used RHEED to study the surface morphology of hydrogen-cleaned GaAs(100) surface.[25] For the InP(100) vicinal surface, RHEED images are evaluated at the in-phase and out-of-phase conditions. The average terrace width and average string length are investigated for the heat-cleaned surface at ~ 300 ^{o}C and after hydrogen cleaning at ~ 380 ^{o}C. Results show that removal of contaminants by atomic hydrogen and accompanied morphology changes improve the electronic surface quality. Correlation between the measured QE and secondary electron-yield with surface morphology detected with RHEED is shown.

II. EXPERIMENT

The InP(100) wafers used in the present study are p-type Zn-doped to provide a carrier density of 3×10^{18} cm^{-3}. The wafers have an etch pit density < 500 cm^{-2} as determined by the manufacturer. The samples are not chemically etched, but only degreased in ethanol before loading in the UHV chamber. The chamber is baked out after loading the sample. The experiments are carried out in a stainless-steel ultrahigh vacuum (UHV) chamber, which is pumped by a 220 *l*/s ion pump. A titanium sublimation pump is also attached to the chamber to reduce the base pressure. The InP substrate is mounted on a molybdenum plate on top of a resistive heater that can be heated up to 600 ^{o}C. The sample is fixed with two molybdenum clamps. A thermocouple is attached to the sample holder close to the sample in order to measure its temperature. A wire is connected to the sample holder to

III- RESULTS AND DISCUSSION

A- Quantum efficiency and secondary electron emission

The preparation of a NEA surface was initiated by cleaning InP(100) in UHV. The chamber was baked for ~ 48 hours to attain a base pressure of ~ 1×10^{-10} Torr, while the InP sample was kept at ~ 350 ^{o}C during baking to reduce surface contamination. RHEED was used to monitor the effect of heat and atomic hydrogen cleaning on the InP(100) surface. The incident electron energy was 9 keV. Activation to NEA was performed by cesium and oxygen deposition. The *yo-yo* procedure was followed.[27] Before surface cleaning, the RHEED pattern showed a halo. This indicates that the surface is covered with hydrocarbons and native oxides. Surface cleaning was started by heating the InP sample at ~ 300 ^{o}C for three hours. The sample temperature was raised gradually (roughly 4-7 ^{o}C per minute) until reaching the desired temperature. The sample was then cooled down to room temperature, activated to NEA, and the QE measured. This surface produced a QE of ~ 0.1% in response to 632.8 nm light. Some diffraction features of the RHEED patterns could be seen. For a heat-cleaned surface at ~ 370 ^{o}C for three hours a QE of ~ 0.2% was obtained. Figure 1(a) shows the RHEED pattern after heat cleaning at ~ 370 ^{o}C.

Next, the QE of the hydrogen-cleaned InP(100) surface activated to NEA was measured along with the secondary electron emission (SEE). After raising the sample to the desired temperature, the hydrogen gas was introduced in the thermal cracker source to produce atomic hydrogen, which interacts with the surface in a down-flow geometry. The SEE was measured after directing the primary electron beam into the surface with an angle of ~ 3.5°. The resultant current was measured before and after activation and the ratio occurs

IV. Conclusion

The effect of atomic hydrogen cleaning on morphology and electron emission performance of the InP(100) surface was investigated. Atomic hydrogen cleaning produces a clean, phosphorus-stabilized (2×4)-reconstructed InP surface. Hydrogen-cleaned surface at 385-400 °C gave a QE of ~ 6% after activation to NEA. A measure of surface contaminants and defect was obtained using the RHEED background-to-peak intensity ratio, $R = (I_p - I_b) / I_b$, at the out-of-phase condition. It is shown that, a higher R surface produces higher QE. Secondary electron emission from the hydrogen-cleaned surface was correlated to the QE. With increased hydrogen cleaning time at 385-400 °C, surface defects due to phosphorus desorption were observed along with a reduction in QE. Quantitative RHEED studies at the out-of-phase condition were used to evaluate the development of surface morphology with hydrogen cleaning.

Acknowledgments

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Figure Captions

Figure (1). RHEED patterns of InP(100) surface. (a) After heat cleaning at 370 ^{o}C, the InP surface is covered with carbon and native oxides. (b) After atomic hydrogen cleaning at ~ 370 ^{o}C with the electron beam incident along the [031] direction. The RHEED streaks become visible along with a strong background.

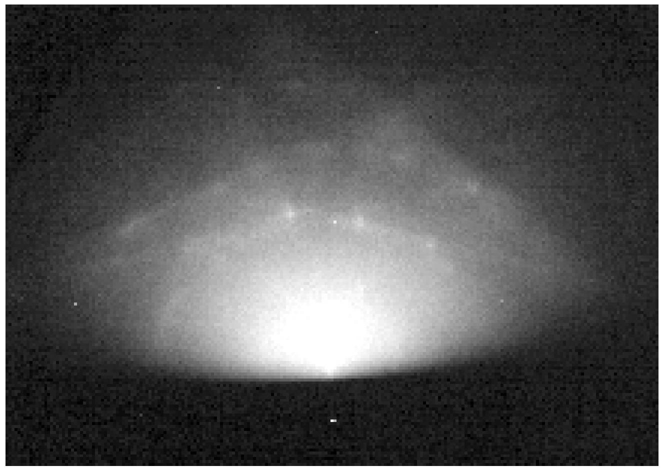
Figure (2). (a) The quantum efficiency and secondary electron emission ratio are measured for a (2×4)- reconstructed InP surface. At each cleaning cycle, the InP sample is cleaned for three hours and the measurements are taken close to room temperature. (b) After hydrogen cleaning at 385-400 ^{o}C, a (2×4) reconstructed surface is obtained. The electron beam is incident along the $[0\bar{1}\bar{1}]$ direction.

Figure (3). After activating the surface with cesium and oxygen, the secondary electron emission is increased with the incident electron energy. Higher secondary-electron yield is obtained, for a surface that produces higher quantum efficiency.

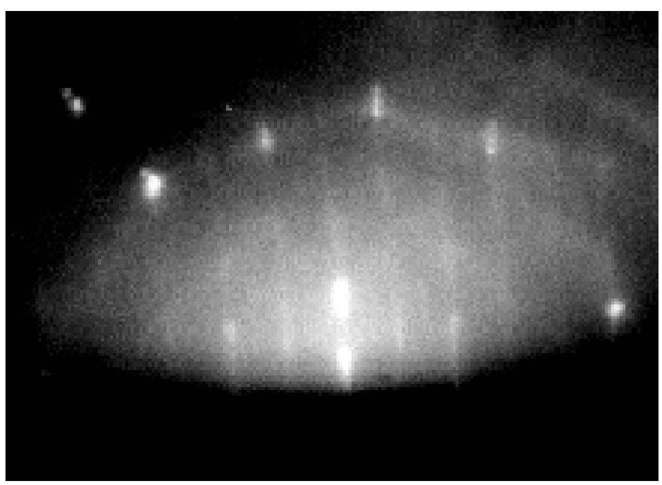
Figure (4). Secondary electrons emission decreases with time after activating the InP surface to negative electron affinity. The measurement is taken after atomic hydrogen cleaning at ~ 370 ^{o}C.

Figure (5). After several hydrogen cleaning at ~ 385-400 ^{o}C, Streaky and spotty RHEED patterns are observed at different locations as shown in (a) and (b), respectively. The electron beam is incident along the [031] direction.

Figure (6). Intensity profiles along the (00) specular RHEED streak showing the in-phase and out-of-phase conditions. The electron beam is incident along the [031] direction.

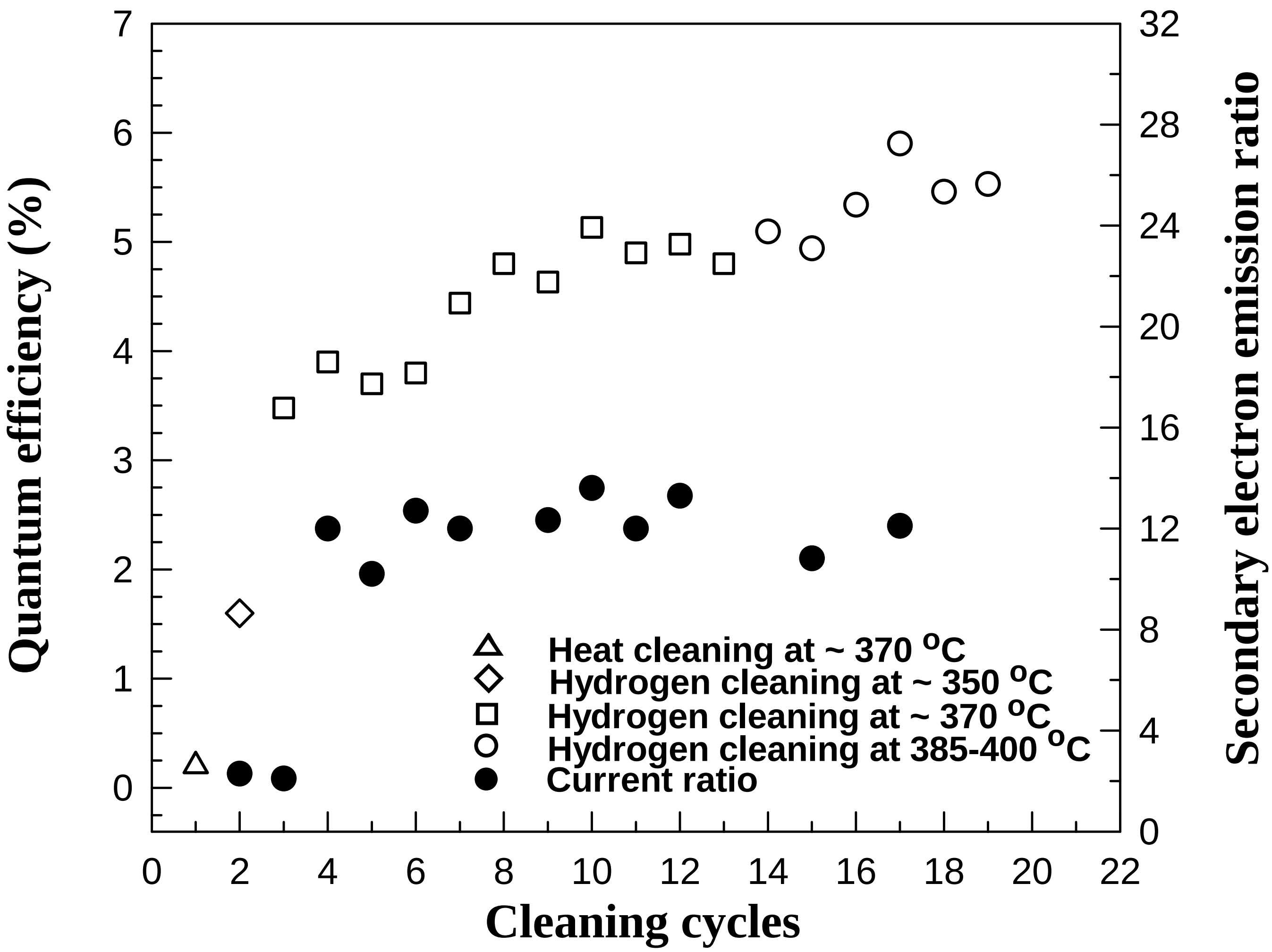


(a)



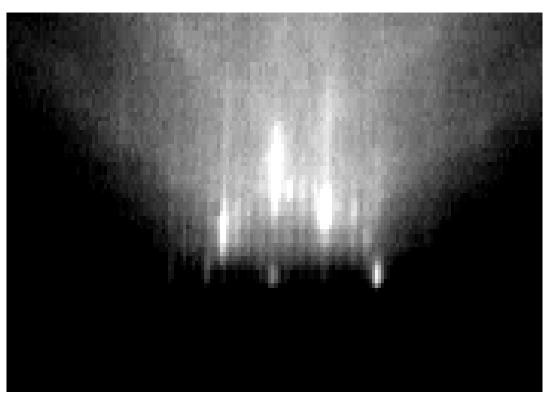
(b)

Figure (1)



Quantum efficiency (%)
Secondary electron emission ratio
Cleaning cycles
Heat cleaning at ~ 370 ^{o}C
Hydrogen cleaning at ~ 350 ^{o}C
Hydrogen cleaning at ~ 370 ^{o}C
Hydrogen cleaning at 385-400 ^{o}C
Current ratio

(a)



(b)

Figure (2)

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Argonne, IL 60439-4871

Dear Sir:

Enclosed please find the revised version of our manuscript "Atomic hydrogen cleaning of InP(100): Electron yield and surface morphology of negative electron affinity activated surfaces," by M. A. Hafez and H. E. Elsayed-Ali. We have revised the manuscript in accordance with the reviewer's comments and enclosed a description of the revisions made.

Sincerely,

Hani Elsayed-Ali
Professor

List of changes to Ms # JR00-2904 by Hafez and Elsayed-Ali

We would like to thank the reviewer for his comments which we have taken in consideration and revised the manuscript accordingly. The following is a list of the major changes we made to the manuscript:

1. We have added a statement in the introduction to distinguish the present manuscript from our previously published papers. In the present manuscript we report for the first time quantitative RHEED study of the surface morphology of hydrogen cleaned InP(100) surface and relate quantitative measures such as RHEED peak-to-background ratio to the observed quantum efficiency (QE) after activation to negative electron affinity (NEA). The previous manuscript we published on atomic hydrogen cleaning of InP(100) [Ref. 9] did not include any quantitative RHEED study of surface morphology. We have published some quantitative RHEED study of hydrogen cleaned GaAs(100) surface [Ref. 25], but that work was not as extensive as reported here and did not include any measurement of secondary electron emission. In addition, clean InP with high electronic quality is a much more difficult to prepare than GaAs due to the low congruent temperature, above which P desorbs preferentially leaving a damaged surface. The development of efficient InP NEA photocathdes have been hindered mainly because of this difficulty.

We have also emphasized the conclusion that the RHEED intensity-to-background ratio R can be effectively used to optimize the surface before activation to NEA. This along with atomic hydrogen cleaning offers a practical methodology for preparation of NEA devices.

2. Part A of Section III was rewritten in accordance with the reviewer’s suggestion. The results are now presented in a more coherent way with one section devoted to the first cleaning cycle, another section discusses the second cleaning cycle on the same sample, a section discussing cycles 3-13 performed at ~ 370 ^{o}C, and a section discussing cycles 14-19 performed at 385-400 ^{o}C.

3. A paragraph was added at the end of Part A of Section III to answer the reviewer’s question on what happens if the sample had not been heat cleaned and our use of cleaning cycles followed by Cs-oxygen activation. We indicated that some heating is always needed during hydrogen cleaning to obtain a clean reconstructed surface. Higher temperatures up to the congruent temperature provided best results. The use of cleaning cycles is made to simply show the progression of the surface quality with cleaning.

4. In the discussion of surface morphology, the heat-treated data points in Figs. 9(b), 9(c), 10(b), and 11 were reported as those at x = 0. We have also added a statement indicating that there was no observed relation between the measured average surface terrace width and observed changes in terrace width distribution with the measured QE and SEE after activation to NEA. We have also redone Fig. 10(a) to show the profiles of the specular RHEED beam in the out-of-phase condition, which is related to the distribution of terrace widths. The FWHM of the split specular peak was reported in Fig.

9(c) in mrad. This in not the case, however, for the RHEED intensity-to-background ratio R, which is a good indication of the resulting QE.

5. We explained that the ratio R is sensitive to both surface contaminants and roughness (mainly add-atom and vacancies). For a clean surface, R provides a measure of the density of surface defects.

6. Significant editing on the writing style and paragraph formatting was done on the manuscript.

7. A statement was added in the conclusion regarding the limitations of the RHEED technique employed in the present study and the need to use other surface sensitive techniques to resolve the nature of the microscopic interactions of atomic hydrogen with the surface.

8. The mechanical deficiencies indicated in the figures were corrected.

From
http://fbox.vt.edu/eng/mech/writing/

Recognizing Run-Ons and Fragments (Basic)

Exercise Contents
Writing Guidelines
Writing Courses

Exercise Links:
Grammar Exercise #2
Grammar Exercise #3
Punctuation Exercises
Usage Exercises

Related Links:
Fragments (Purdue)
Run-Ons (Purdue)

The sentence is the fundamental unit of expression in professional writing. To maintain credibility as a professional, you have to know what constitutes a sentence. In the exercise below, identify whether each of the highlighted word groups is a sentence (S), fragment (F), or run-on (RO). Note that a run-on is a specific grammatical term referring not to a long sentence, but to a group of words containing two or more independent clauses that are incorrectly joined. Once you have clicked on the right answer, you will view a discussion. Corresponding information for this exercise can be found in *The Craft of Editing* (denoted *CE*) and *The Craft of Scientific Writing* (denoted *CSW*). Note: In the general preferences of your browser, please do not override this document's choice of font colors.

These exercises work best with Netscape.

Original: Although the shock sphere is still strong at the end of the fireball's life, the sphere is no longer strong enough to heat the air to incandescence.

Discussion: No grammatical mistake exists. This group of words is a sentence with an introductory dependent clause coupled to an independent clause.

Original: At that point the shock sphere is no longer strong enough to heat the air to incandescence, however, the sphere is still very strong.

Revision: At that point, the shock sphere is no longer strong enough to heat the air to **incandescence. However,** the sphere is very strong.

Discussion: The original was a run-on. The adverb "however" cannot join two independent clauses. Note that several ways exist to correct this run-on. Also note that beginning a sentence with "however" is not an error. More discussion exists in *CE* (pages 115 and 129) and *CSW* (259, 270).

Original: At the end of the fireball's life, the shock sphere no longer being strong enough to heat the air to incandescence.

Revision: At the end of the fireball's life, the shock sphere **is** no longer strong enough to heat the air to incandescence.

Discussion: The original was a fragment without a verb. The verb "is" makes this group of words a sentence. More discussion exists in *CE* (page 111).

Punctuation Exercise #1 (Commas)

Exercise Contents
Writing Guidelines
Writing Courses

Exercise Links:
Punctuation Exercise #2
Grammar Exercises
Usage Exercises
Advanced Exercises

In the following sentences, click on the places where the comma is undesired, is missing, or should be changed to another piece of punctuation. Note that each sentence has at most one punctuation error. If no error exists, click on "No error." Corresponding information for this exercise can be found on pages 261-267 in *The Craft of Scientific Writing.* Note: In the general preferences of your browser, please do not underline links and do not override this document's choice of font colors.
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1. The new material, which will be available next week is composed of plastic and iodine.

   Revision: The new material, which will be available next **week, is** composed of plastic and iodine.

   Discussion: missing parenthetical comma for "which" clause.

2. As World War II escalated the United States became locked into a race with Germany to develop the first atomic bomb.

   Revision: As World War II **escalated, the** United States became locked into a race with Germany to develop the first atomic bomb.

Discussion: missing comma following introductory clause. Note that without the comma, the reader does not know where the introductory clause ends.

3. The three largest earthquakes occurred in San Francisco, Tokyo, and Lima.

   Original: The three largest earthquakes occurred in San Francisco, Tokyo, and Lima.

   Discussion: While the comma following "Tokyo" is optional, it is certainly not incorrect.

4. On February 5, 1990 Mount St. Helens had another eruption, this one smaller than the eruption 10 years before.

   Revision: On February 5, **1990, Mount** St. Helens had another eruption, this one smaller than the eruption 10 years before.

   Discussion: missing parenthetical comma. The year "1990" is parenthetical information about the date February 5. Although some publications treat this comma as optional, many more (including the *Wall Street Journal* and the *New York Times)* do not. Note that if the date had been written as "5 February 1990," then a simple comma following "1990" would have been appropriate. Also note that the comma following "eruption" is correct because what follows is a phrase.

5. Every year, an earthquake of magnitude between 8.0 and 8.9 on the Richter scale, will be experienced somewhere in the world [Haughton, 1989].

   Revision: Every year, an earthquake of magnitude between 8.0 and 8.9 on the Richter **scale will** be experienced somewhere in the world [Haughton, 1989].

   Discussion: undesired comma. Note that while the comma following "year" is optional, it is certainly not incorrect. Also note that the punctuation for the reference listing at the end of the sentence depends upon the format.

6. As the flame front propagates hot combustion products expand, resulting in a rapid pressure increase.

   Revision: As the flame front **propagates, hot** combustion products expand, resulting in a rapid pressure increase.

   Discussion: missing comma following the introductory clause. Without the comma, the audience does not know when the clause ends.

7. The concentrations of these gases, which are called

greenhouse gases control how much infrared radiation escapes.

Revision: The concentrations of these gases, which are called greenhouse **gases, control** how much infrared radiation escapes.

Discussion: missing parenthetical comma for the "which" clause.

8. After 1987 parachuting accidents decreased significantly because instructors started teaching novices with tandem jumps rather than static lines.

   Revision: After **1987, parachuting** accidents decreased significantly because instructors started teaching novices with tandem jumps rather than static lines.

   Discussion: missing comma following the introductory phrase. Without the comma, the audience trips.

9. On May 18, 1980, a cloud of hot rock and gas surged northward from Mount St. Helens.

   Revision: On May 18, 1980, a cloud of hot rock and gas surged northward from Mount St. Helens.

   Revision: This sentence is punctuated correctly.

10. The synergistic reactor contains a chamber in

which the exhaust from the burning coal mixes with limestone, see Appendix A.

Revision: The synergistic reactor contains a chamber in which the exhaust from the burning coal mixes with **limestone, as discussed in** Appendix A.

Discussion: The original is a run-on. One solution (given here) is to make the reference to Appendix A a verb phrase. Another solution is to create a separate sentence. Still a third is to use parentheses to refer to Appendix A.

11. The local economy should benefit from the operation. Local property taxes would decrease for area residents and the Nicolet Minerals Company, formally the Crandon Mining Company, is expected to spend more than $40 million on local good and services.

Revision: The local economy should benefit from the operation. Local property taxes would decrease for area **residents, and** the Nicolet Minerals Company, formally the Crandon Mining Company, is expected to spend more than $40 million on local good and services.

Discussion: Without the comma before "and," the audience doesn't know where the first independent clause ends and the second one begins.

Punctuation Exercises #2 (Colons, Semicolons, and Dashes)

Exercise Contents
Writing Guidelines
Writing Courses

Exercise Links:
Punctuation Exercises #1
Grammar Exercises
Usage Exercises
Advanced Exercises

In the following sentences, click on the places where punctuation is undesired, is missing, or requires change. Mistakes include missing, unwanted, or misplaced colons, semicolons, parentheses, and quotation marks. Note that each sentence has at most one punctuation error. If no error exists, click on "No error." Corresponding information for this exercise can be found on selected pages of *The Craft of Editing* (denoted as *CE*) and pages 261-267 in *The Craft of Scientific Writing*. Note: In the general preferences of your browser, please do not override this document's choice of font colors.

These exercises work best with Netscape.

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1. The three largest earthquakes occurred in: San

Francisco, Tokyo, and Lima.

Revision: The three largest earthquakes occurred **in** San Francisco, Tokyo, and Lima.

Discussion: undesired colon (it breaks a continuing thought). Note that while the comma following "Tokyo" is optional, it is certainly not incorrect. (*CE*, p. 103)

2. According to Dr. D. Simpson [1986], a biologist at the Harvard Medical School, "Only 30,000 rads are needed for interphase death to occur in yeast cells".

   Revision: According to Dr. D. Simpson [1986], a biologist at the Harvard Medical School, "Only 30,000 rads are needed for interphase death to occur in yeast **cells."**

   Discussion: Quotation marks appear outside commas and periods in the United States. (*CE*, pp. 124-125)

3. The synergistic reactor contains a chamber in which the exhaust from the burning coal mixes with limestone; see

Appendix A.

Revision: The synergistic reactor contains a chamber in which the exhaust from the burning coal mixes with **limestone, as discussed in** Appendix A.

Discussion: A semicolon cannot join the two independent clauses because what would be on the left side of the semicolon (a sentence in the indicative mood) would not be parallel to what is on the right side (a sentence in the imperative mood). One solution (given here) is to make the reference to Appendix A a verb phrase. Another solution is to create a separate sentence. Still a third is to use parentheses to refer to Appendix A. (*CE*, p. 130)

4. The synergistic reactor contains a chamber in which the exhaust from the burning coal mixes with limestone - see Appendix A.

   Revision: The synergistic reactor contains a chamber in which the exhaust from the burning coal mixes with **limestone--see** Appendix A.

   Discussion: The em-dash can be represented by two hyphens, but not one as in the original. (*CE*, pp. 106-107)

5. The synergistic reactor contains a chamber in which the

exhaust from the burning coal mixes with limestone(See Appendix A.)

Revision: The synergistic reactor contains a chamber in which the exhaust from the burning coal mixes with **limestone (see Appendix A).**

Discussion: The punctuation associated with the parentheses was incorrect. First a space precedes the left parenthesis. Second, for parenthetical expressions that are part of the sentence, the first word is not capitalized. Finally, for parenthetical expressions that are part of the sentence, the sentence's punctuation (a period in this case) appears outside the parentheses.

- The absorption *A* is calculated by:

$$A = 1 - kR,$$

where *k* is the correction factor and *R* is the measured reflectance.

Revision: The absorption *A* is calculated **by**

$$A = 1 - kR,$$

where *k* is the correction factor and *R* is the measured reflectance.

Discussion: undesired colon (it breaks a continuing thought). Note that if the words "the following" had followed the word "by," then the colon would have been correct. (*CE,* p. 108)